Title of Thesis : Studies of Disturbances in the F-region of the Ionosphere.

Name of candidate : (Mrs) Girija Rajaram

Thesis adviser : Professor R.G.Rastogi
Physical Research Laboratory
Ahmedabad
India.

Submitted to : Gujarat University
for
the degree of
Doctor of Philosophy.

043
B4324

December 1971

Physical Research Laboratory

Ahmedabad

India

Dedicated to

My Father and Mother

PREFACE

Magnetic storms are violent disturbances of the earth's upper atmosphere caused by enhanced electromagnetic and corpuscular radiations from the sun. A 27 - day recurrence pattern in storms, their effect on the earth's magnetic field and on the propagation of radio waves, their association with sunspots, the sudden brightening of solar spectral lines, and the 11-year solar cycle - all these features and more have come into recognition over the last century, and are being unravelled further by the recent entry of rockets and satellites into the realm of space.

The F-region of the earth's ionosphere is one of the most sensitive indicators of geomagnetic disturbances and is the subject of investigation of the present Thesis. All over the world, the F-region experiences vast changes of electron density, an increase or decrease depending on the latitude and season concerned. The electron density often takes a few days after the storm commencement to return to normal, and shows a relationship in behaviour with the course of the corresponding magnetic variations. Since the earliest observations of storm effects on the F-region by Appleton and Ingram in 1935, a large number of workers have investigated the morphology of F-region disturbances, and have attempted to explain the mechanism causing these disturbances. However, no single theory has been able to successfully explain the variations observed at all latitudes of the earth.

One of the causes of this is the complexity of the normal undisturbed quiet F-region itself; it does not obey a simple solar zenith angle control as the lower ionospheric layers do. At these heights of 300 km and more, the gyrofrequency of electrons and ions greatly exceeds the collision frequency with neutral particles, and the geomagnetic field excercises a powerful control on the diffusion of charged particles. Movements of ionisation are also influenced by the thermospheric wind systems existing at these heights and by the interaction of the existing electric fields and the geomagnetic field. The chemical reactions and ion composition here are rather sensitive to temperature changes. Needless to say, the behaviour of the disturbed F-region is still more complicated.

The F-region is controlled by the magnetic dip at the location concerned, but often stations having the same dip angle experience different f_oF_2 behaviour because of the general configuration of the geomagnetic field of the area; for example f_oF_2 at some South American stations differs considerably from that at North American stations with the same dip. Hence special care was taken in the present analysis, to isolate these regional anomalies which have not been given consideration in ionospheric studies so far.

The approach of the present work has been to study the F-region storm effects in detail at all latitudes for two particular longitude zones - the West or American zone centred around

75°W with its low geomagnetic field intensity and asymmetrical orientation of magnetic dip, and the East or Australasian zone centred around 75° E with its high geomagnetic field intensity, and symmetrical iso-dip configuration. The longitudinal differences in F-region storm behaviour with respect to season, solar cycle epoch, latitude, and time of commencement of storm, have been brought out. A precise determination of the degree of F_2 disturbance at the different latitudes of a particular longitude zone and the exact latitude of change-over of "positive" to "negative" type of disturbances, has been possible by taking stations closely-spaced in dip. Information on the geomagnetic and the seasonal anomalies of the F_2 region during Quiet and Disturbed conditions has been obtained. Electron density distributions at true heights have been computed from original ionograms of equatorial stations lying in the two longitude zones, for different seasons and solar cycle epochs, for both magnetically Quiet and Disturbed conditions.

The present studies of ionospheric storms individually at a large number of stations without grouping them into arbitrary latitude zones, has brought to light some new facts about F_2-region storm behaviour which were masked by the previous methods of analyses. It is shown clearly that the daily variation of f_oF_2 and the N-h profiles at an equatorial station during magnetically quiet days is greatly controlled by the equatorial electrojet current. Apart from the increase in f_oF_2 at equatorial

stations and the decrease at high latitudes well-known to be caused by geomagnetic storms, it has been realised that a certain band of winter latitudes centred around 55° dip experience the largest enhancements of f_oF_2. This increase is larger by night than by day, and is greater in the American Zone than in the Asian Zone. Equatorial stations in the American Zone show an unexpected decrease of f_oF_2 during disturbed periods of the southern solstitial months. Additional solar cycle effects in the general ionospheric storm behaviour have been shown. It is found that magnetic disturbances have a tendency to level out most anomalies of the normal F_2 region.

All these results indicate that the magnetically-disturbed F-region is influenced by various geophysical processes occurring simultaneously, apart from mere geomagnetic field changes. It has been suggested that storm-time changes in F_2 ionisation within the Appleton anomaly region are primarily caused by the weakening of equatorial electrojet fields. This weakening decreases the electrodynamic drift over the equator, thereby increasing equatorial f_oF_2, and depriving stations at the anomaly crest of transported ionisation. The auroral regions are subject to vast temperature changes caused by particle precipitation and Joule currents. This causes large thermal and pressure gradients, giving rise to equatorward wind systems, which combine with the normal thermospheric winds to form the vast winter enhancement of F_2 ionisation around 55° dip. The highest latitudes are subject to temperature effects, and polar winds which blow ionisation into the magnetospheric tail.

Thus the observed F_2 storm effects are the combined effect of these complex processes, the magnitude of each of which depends on the degree of geographic and geomagnetic control at the latitude concerned. The relative importance of these processes could also vary from storm to storm.

This Thesis consists essentially of three parts:

1. An introduction to the Solar-Terrestrial environment during both Quiet and Disturbed conditions.
2. The Morphology of the quiet F-region. This deals with the various F_2 anomalies, world wide variations of f_oF_2, and electron density distributions at true heights for magnetically quiet conditions of high and low sunspot epochs.
3. Studies of the Disturbed F-region which forms the major part of the work. Observations which support the idea of weakening of equatorial electric fields during magnetic storms and disturbances are given. The concluding chapter discusses the possible causes of the disturbed F_2 behaviour.

Papers on the relevant subject matter, which have been published in scientific journals, are included where appropriate.

It is hoped that the identification of these departures of ionospheric storm behaviour from the classical picture will help in the understanding of the processes themselves which cause these storms.

R.G. Rastogi

(R.G. Rastogi)
Thesis Adviser

Girija Rajaram

(Girija Rajaram)
Author

A C K N O W L E D G E M E N T S

I wish to express my deep gratitude to my Guide , Professor R.G.Rastogi for introducing me to the subject of this Thesis, and for his inspiring and encouraging guidance throughout. I thank Dr. A.C. Das for discussions which have helped me immensely in understanding the physics of the magnetosphere and the earth's outer ionosphere. I am grateful to Professor K.R. Ramanathan for his kind and continued interest in my work, and his stimulating suggestions. Dr. J.S. Shirke spared many hours of his valuable time in discussion during the writing-up of the Thesis. I am happy to acknowledge the cheerful and willing help of Miss Suchita B. Thakore in the large amount of computational work involved.

My thanks go to all the members of our group for their co-operative attitude throughout, for a work of this nature is rarely the product of an individual's sole effort. The Computing Centre at the Physical Research Laboratory has been invaluable in efficiently processing the vast amount of data used. I am grateful to the Draughting and Photographic sections of the Laboratory for their aid at the different stages.

I wish to express my gratitude to Dr. M.K. Vainu Bappu, Dr. J.C. Bhattacharya, and other members of the Indian Institute of Astrophysics, Kodaikanal, for their hospitality, and facilities extended towards studying their excellent ionograms and other data at Kodaikanal. The World Data Centre A (NOAA) atBoulder Colorado, has been prompt and understanding in providing us with whatever data we required.

A word about family members may not be out of place. My late grandfather Sri C.P. Narayanan was instrumental in introducing me to the fascinating realm of Physics. My sister Miss Manjula Subramaniam has been a source of encouragement at the most-needed hours. I thank my husband Sri P.N. Rajaram for his understanding and co-operation throughout; and my little daughter Deepanjali for agreeing to let her mother work undisturbed.

My thanks go to Dr. R.P. Sharma for reading the manuscript and for suggestions regarding the same. Dr.Harish Chandra and Mr. P. Raghavan have been of great help at various stages of the work. Mrs. Rhoda Bharucha has given me her staunch and friendly support at all times of need. Mr. Francis Paul has done a good and neat job of typing the Thesis.

Finally I thank the Ministry of Education, Government of India for a Research Scholarship, and the Physical Research Laboratory for all the facilities it has extended towards this study.

(GIRIJA RAJARAM)

C O N T E N T S

		Page
Preface		i
Acknowledgements		vi
CHAPTER - I	- THE SOLAR TERRESTRIAL ENVIRONMENT	
1.1	Introduction	1
A	THE QUIET SUN-EARTH ENVIRONMENT	
1.2	The Earth's magnetosphere	2
1.3	The earth's atmosphere	5
1.4	Solar radiations	6
1.5	Interaction of solar radiations with the earth's atmosphere	8
1.6	The Earth's magnetic field	10
1.7	The quiet-day variations of the geomagnetic field, and the dynamo theory	13
1.8	The equatorial electrojet	15
1.9	Geomagnetic field parameters at earth's surface	17
B	THE DISTURBED SUN-EARTH ENVIRONMENT	
1.10	Disturbed solar emissions	20
1.11	The disturbed geomagnetic field	22
1.12	Disturbance effects in the ionosphere	24
1.13	The indices of geomagnetic activity	26

Page

CHAPTER - II - THE MORPHOLOGY OF THE QUIET F-REGION

2.1 Introduction 28

2.2 Chemistry of the F-region 30

2.3 Dynamics of the F-region 33

2.4 Thermospheric wind effects in the F-region 36

2.5 F_2 region anomalies 38

(a) Annual variation 39

(b) Semi-annual variation 39

(c) The geomagnetic anomaly 40

(d) The seasonal anomaly 44

2.6 World-wide variations of Quiet-day f_oF_2 46

ELECTRON DENSITY DISTRIBUTIONS AT TRUE HEIGHTS HEIGHTS ON QUIET DAYS.

2.7 Solar cycle and seasonal studies at equatorial station Kodaikanal 49

(a) Daily variation of $h_{max}F_2, y_m, N_T, N_{max}F_2$ 49

(b) Changes in $h_{max}F_2$, y_m, $N_{max}F_2$ from low to high sunspot 51

(c) Contours of constant electron density 52

(d) Electron density variations at constant heights 54

2.8 Longitudinal differences in electron density distributions at equatorial stations 55

(a) Comparison of $h_{max}F_2$, y_m, N_T and $N_{max}F_2$ 56

Page

(b) Comparison of constant electron density contours 57

(c) Comparison of electron density distributions at constant heights. 59

CHAPTER - III - METHODS OF ANALYSES AND GENERAL REVIEW OF F- REGION DISTURBANCES

3.1 Introduction 61

(a) $D_{st}(f_oF_2)$ - disturbance storm-time 62

(b) DS (f_oF_2) -disturbance local time inequality 64

(c) SD (f_oF_2) -solar daily disturbance 65

(d) N-h studies -true height profiles of electron density 66

3.2 Review of earlier work on bottomside F-region 67

3.3 Review of topside studies of F-region 71

(a) Methods of topside probing 72

(b) Topside during Quiet conditions 73

(c) Topside during Disturbed conditions 74

CHAPTER - IV - STUDIES OF THE DISTRUBED F-REGION

4.1 Introduction 79

4.2 Seasonal $D_{st}(f_oF_2)$ variations at equatorial, low, mid, and high latitudes. 80

		Page
4.3	North-south asymmetry in storm-time variation of f_oF_2	86
4.4	Explanation of North-South asymmetry in D_{st} (f_oF_2)	88
4.5	D_{st} (f_oF_2) dependence on time of storm-commencement — equatorial, low, mid and high-latitudes	89
4.6	f_oF_2 variations on magnetically Quiet and Disturbed days - S_q (f_oF_2) and S_d (f_oF_2)	93
	(a) Solar cycle differences	96
	(b) Longitudinal differences	98
4.7	Equatorial electron density distributions during Quiet and Disturbed conditions	101
	(a) Studies at Thumba	
	(i) Variations of $h_{max}F_2$, y_m, N_T, $N_{max}F_2$	101
	(ii) Iso-electron density contours during Q and D days.	103
	(iii) Electron density distribution at constant heights	106
	(b) Studies at Huancayo	
	(i) Variations of $h_{max}F_2$, y_m, N_T, $N_{max}F_2$	107
	(ii) Iso-electron density contours during Q and D days	109
	(iii) Electron density distributions at constant heights	110
4.8	Longitudinal differences in Quiet and Disturbed day behaviour of equatorial electron density distributions	111

Page

(a) Comparison of $h_{max}\ F_2$, y_m, N_T 112

(b) Comparison of electron density distributions at constant heights 114

4.9 Conclusions 115

CHAPTER - V - LATITUDINAL VARIATION OF DISTURBED f_oF_2 PARAMETERS

5.1 Introduction 119

5.2 Latitudinal variation of $D_m(f_oF_2)$ 120

(a) Longitudinal differences 121

(b) Conclusions 123

5.3 Longitudinal differences in $D/Q(f_oF_2)$ 124

(a) Midday hours 125

(b) Midnight variations 127

(c) Conclusions 128

5.4 Solar cycle variations in $D/Q(f_oF_2)$ and average f_oF_2 129

(a) Midday hours 130

(b) Midnight hours 131

(c) Conclusions 131

Page

5.5 Time variations of SD (f_oF_2)

(a) Longitudinal variations in SD(f_oF_2)- high sunspot 133

(b) Solar cycle variations in SD (f_oF_2) 136

(c) Conclusion 138

5.6 Diurnal development of the latitudinal variation of (D-Q) (f_oF_2) 139

5.7 The geomagnetic anomaly on magnetically Quiet and Disturbed days. 142

5.8 The seasonal anomaly on magnetically Quiet and Disturbed Days 148

(a) Solar cycle variations of the seasonal anomaly

(i) Midday hours 148

(ii) Midnight hours 151

(iii) Conclusions 152

(b) Longitudinal variations in seasonal anomaly during high sunspot 154

(i) Midday hours 155

(ii) Midnight hours 156

(iii) Conclusions 157

Page

CHAPTER - VI - ELECTROJET EFFECTS ON THE EQUATORIAL AND LOW-LATITUDE F-REGION MAGNETICALLY QUIET AND DISTURBED DAYS

6.1 Introduction 158

6.2 Relationship between equatorial electrojet and low-latitude F_2-ionisation-high sunspot 160

6.3 Quiet day f_oF_2 variations at anomaly crest and trough for strong and weak electrojet 162

6.4 Relationship of $\Delta H_T - \Delta H_A$ with Δf_oF_2 at anomaly crest and trough 163

6.5 Quiet-day equatorial electron density distributions for Strong and Weak electrojet 165

(i) Electron density at constant heights 165

(ii) N-h profiles 166

(iii) Variations of $h'_{max}F_2$, y_m, N_T, $N_{max}F_2$ 168

6.6 Electrojet effects on F_2 critical frequencies associated with geomagnetic storms 169

6.7 Electron density distributions at anomaly crest and trough for a geomagnetic storm 172

(i) Electron density at constant heights 173

(ii) N-h profiles 174

(iii) Variations of $h_{max}F_2$, y_m, N_T, $N_{max}F_2$ 175

6.8 Conclusions 178

Page

CHAPTER - VII - CONCLUSIONS

7.1 Current ideas on F-region ionospheric storm-mechanisms 179

(a) Electrodynamic drift effects 179

(b) Thermal effects 180

7.2 Outstanding features of disturbed F_2 region behaviour 182

7.3 Electric fields and thermospheric wind systems associated with magnetically disturbed conditions 184

(i) Electric fields 184

(ii) Heating effects 187

(iii) Wind systems 189

7.4 Disturbed F_2 behaviour in high sunspot years 191

7.5 Disturbed F_2 behaviour in low sunspot years 199

7.6 Electron density distribution studies 205

7.7 Suggestions for future work 206

7.8 Epilogue 208

REFERENCES

CHAPTER - I

THE SOLAR TERRESTRIAL ENVIRONMENT

"मित्रो दाधार पृथिवीं उतद्याम्
मित्रः कृष्टीरनिमिषा अभि चष्टे" — ऋग्वेद

" Mithro Dadhaara Prithiveem Uthadhyaam
Mithrah Krishteeranimisha Abhi Chashtē "

- Rig Veda

" The Sun sustains the Earth and the Sky
And activates all Creation with unwinking eye! "

1.1 Introduction

The earth is under the gravitational control of the sun, and is immersed in the electromagnetic and corpuscular radiations which flow from it. It is the interaction of these radiations with the rotating earth's atmosphere and its geomagnetic field which gives rise to the wide variety of upper atmospheric phenomena observed on earth. These include the formation of the magnetosphere and ionosphere, the geomagnetic variations arising from atmospheric current systems, magnetic storms, aurorae, airglow, red arcs, variation in solar wind and in cosmic rays, etc. The effect of magnetic storms on the ionospheric F-region is the subject of investigation of the present thesis and these processes require a knowledge of the Sun-Earth environment during both magnetically quiet and disturbed conditions. The main features of this environment are therefore summarised in this chapter.

A - THE QUIET SUN-EARTH ENVIRONMENT

1.2 The earth's magnetosphere

Fig. 1.1 (Pg. 2 (a)) gives a picture of the earth's environment as deduced from various satellite observations (O'Brien, 1967). Outer space can be classified broadly into 3 regions:-

1. Interplanetary space - which is the domain of the solar wind and solar magnetic fields and is unaffected by the presence of the earth and its magnetic field.
2. The magnetosheath - the region of turbulent interaction between the solar wind and the geomagnetic field.
3. The magnetosphere - the cavity containing the earth's magnetic field and ionised gas in which the geomagnetic field strongly influences the dynamics of the ionised gas and energetic particles.

These three regions of space are separated by two surfaces —— the shock-wave surface which isolates the interplanetary medium from the magnetosheath, and the magnetopause separating the magnetosheath from the magnetosphere.

The earth's normal dipole field is distorted by the solar wind, to compress it to about 10 R_e on the dayside, and draw it out into a tail on the nightside, often extending beyond 60 R_e (Cahill and Amazeen 1963). The outer boundary of the

2(a)

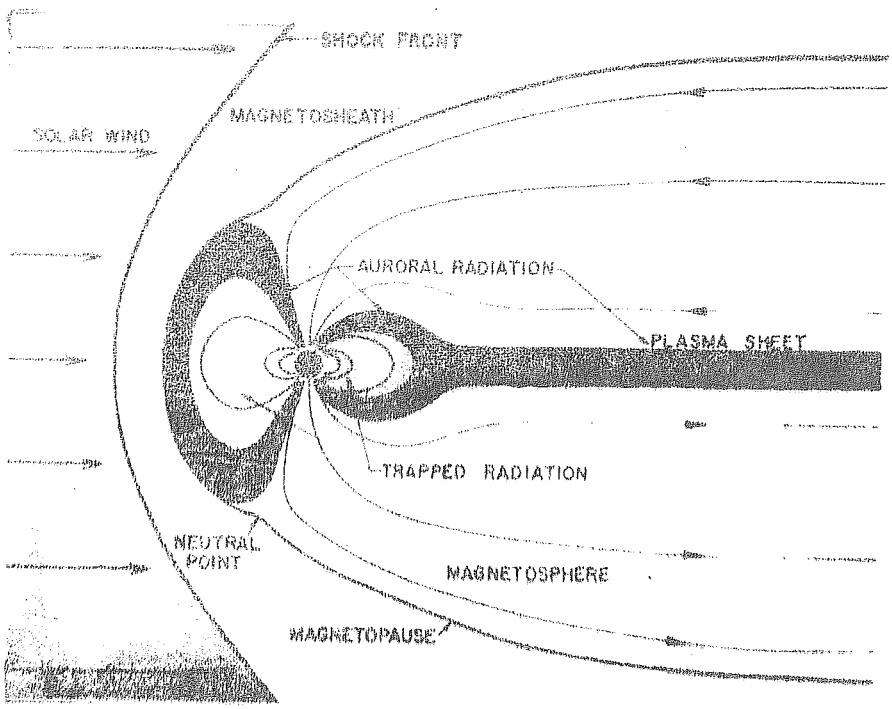


Fig. 1.1 The earth's magnetosphere(O'Brien 1966)

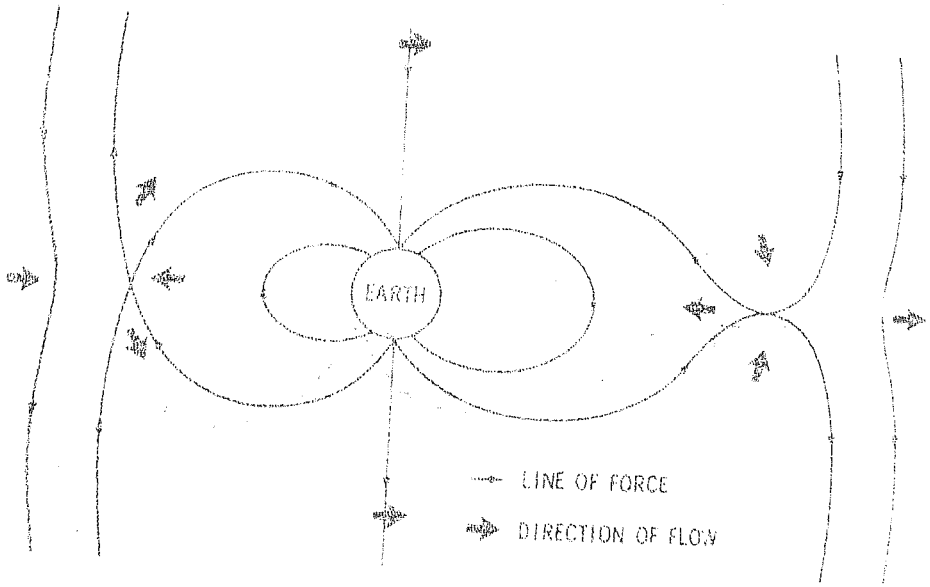


Fig. 1.2 Dungey's model of the magnetosphere (Dungey 1961). Note the earth's field lines connecting up with the interplanetary field lines.

magnetosphere is the magnetopause and is formed where the energy density of the solar wind is equal to the energy density of the magnetic field

$$\frac{1}{2}\rho V^2 = B^2/8\pi$$

ρ - Solar wind density

V - Solar wind velocity

B - Intensity of earth's field at magnetopause

Dungey (1958, 1961) suggested that especially at disturbed times, the earth's polar field lines connect with the interplanetary field lines so that interplanetary matter has direct access to the earth's atmosphere in these regions (see Fig. 1.2 (Pg. 2(a)). There is no well-defined magnetopause in this model, and there are two neutral points, one near the subsolar point and one at the back side of the magnetosphere.

Solar matter can directly enter the earth's atmosphere through (1) the two horns around the neutral points (N.P.) on the magnetopause centred at 67° geomagnetic latitude on the dayside, and (2) the open tail on the nightside.

These regions of direct access of interplanetary matter are the regions where displays of light (often brilliant) called Aurorae occur, and are shown in the diagram as the Auroral Radiation regions.

The neutral plasma sheet is a low field-strength plasma sheet which separates the oppositely-directed field lines in the tail, and a region of low-energy electrons is found here.

The earth's radiation belts are regions where charged particles are trapped by the earth's magnetic field and are called the Van Allen radiation belts (Van Allen 1959).

The radiation belts are found to consist of two main zones:

1. The inner zone or the proton belt, with maximum particle flux of $E > 30$ Mev at a distance of about 1.5 R_e in the equatorial plane (Freden and White, 1959; Fan et al., 1960). This zone is fairly stable in time.

2. The outer zone or electron belt situated beyond 2 R_e and extending to almost 10 R_e. The energy of the particles is < 1.5 MeV and the particle flux is highly variable particularly during magnetic disturbances.

The charged particles execute complex motions under the influence of the geomagnetic field - a gyration about the field lines, a bouncing back and forth along the field lines, and a slow drift in longitude around the earth, all executed simultaneously. Each of these motions has an adiabatic invariant associated with it (Alfvén 1950; Northrup and Teller 1960).

From a maximum of about 10^6 electrons/cm^3 at the ionospheric F_2 peak (400 km), the electron density gradually decreases with altitude through 10^4 electrons/cm^3 at 1000 km., 10^3 electrons/cm^3 at 10,000 km to about 10 electrons/cm^3 at 100,000 km. Beyond the magnetosphere, interplanetary space contains 1-10 electrons/cm^3.

1.3 The earth's atmosphere

The earth's atmosphere is the tenuous mass of gas surrounding the earth. It extends a few earth radii up to the magnetopause where it merges with interplanetary space. It is chiefly a mixture of molecules of nitrogen, oxygen, carbon dioxide, argon, and other rare gases at ground level, decreasing in density and changing from molecular to atomic and ionic species with increasing height.

The upper atmosphere commences from a height of 60 km. Its volume is a few thousand times the volume of the earth, though its mass is less than a thousandth of the total atmospheric mass. It is the seat of various phenomena, such as a particular temperature distribution, an ionosphere, chemical reactions, flow of currents, winds and radiations. Upto above 90 km, the pressure, density and temperature variations are well-known from rocket studies. Between 90 km and 200 km the techniques of measurement employed below 90 km do not work too well; the atmospheric properties here are more variable and less known. Above 200 km where satellites can orbit for days together, the properties are better defined.

This upper atmosphere can be classified with height on the basis on its (1) temperature (2) chemical composition or (3) ionisation distribution. These classifications are shown in Fig. 1.3 (Pg. 6 (a)) and the various regions can be clearly seen. A hydrostatic equilibrium between the pressure gradient and the force of gravity governs the decrease of gas density with height.

Below 80 km large-scale atmospheric circulations keep the atmosphere well-mixed. At about 105 km (the homopause) the mixing decreases rapidly, and the photochemical dissociation of molecular oxygen into its lighter atomic form commences. Above this there is reduced turbulence, increased molecular dissociation, and the gases are in diffusive equilibrium. At 300 km atomic oxygen replaces molecular nitrogen as the dominant component, at 1000 km helium becomes the major component, and beyond 2500 km hydrogen takes over.

1.4 Solar radiations

Solar radiations are of prime importance in upper atmospheric physics as they are the main source of almost all the energy which flows into the atmosphere. Situated at a distance of 149×10^6 km from the earth, the quiet sun radiates as a blackbody at a temperature of around $6000^{\circ}K$ (to a first approximation).

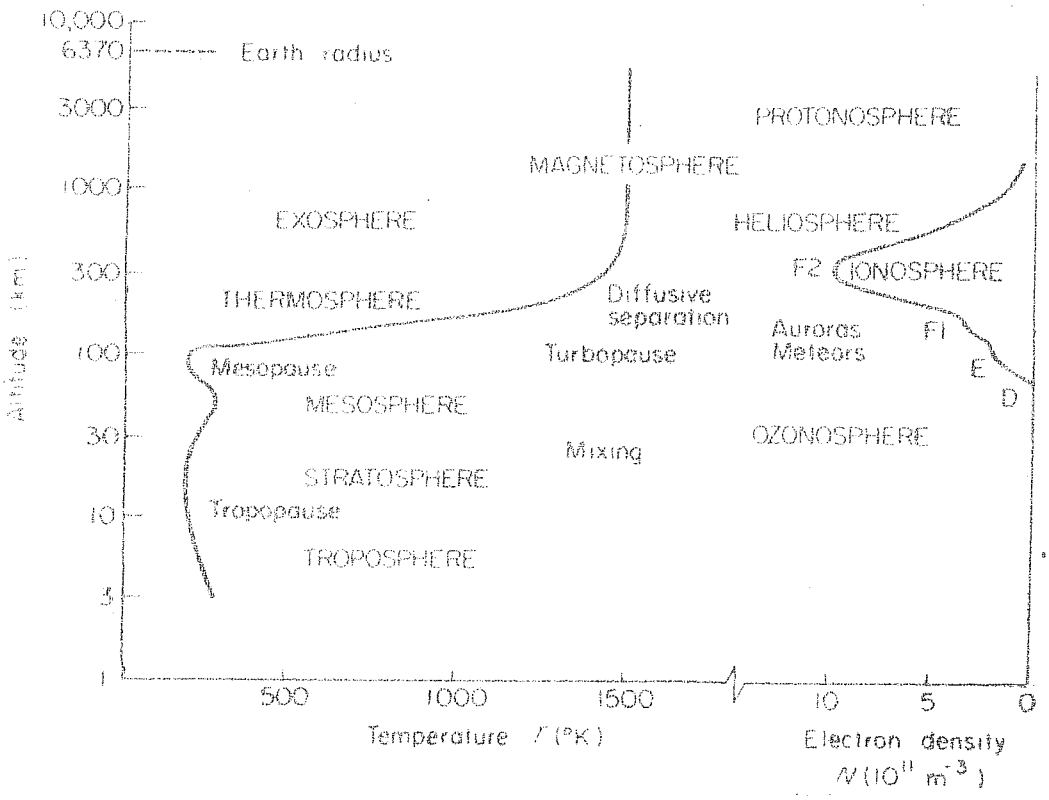


Fig.1.3 Regions of the earth's atmosphere (Rishbeth and Garriott 1969).

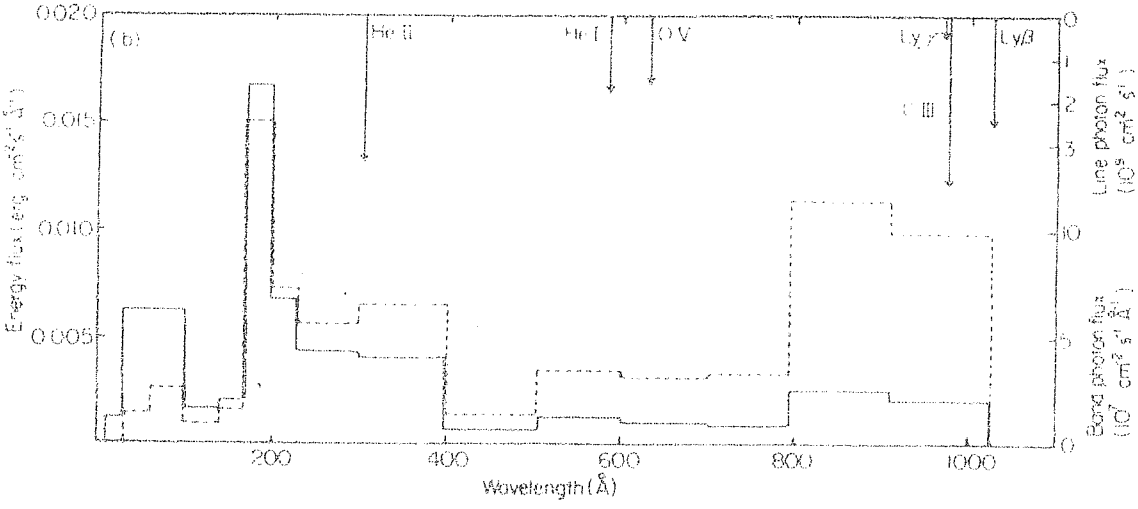


Fig. 1.4 Solar flux between 8 and 1027 A° for moderate level of activity (Allen 1965).

The solar electromagnetic spectrum extends from wavelengths of less than 1 A° to more than 10 meters, with X-rays at the lowest end, through Ultra-violet, Optical, Infrared, and at the highest end Radio Emissions. Superimposed on the black-body continuum are certain lines characteristic of the solar elements, some of these being Hydrogen α (6563 A°), Lyman α (1216 A°), and Helium 1 (584 A°). The solar photon flux with some important spectral lines is shown in Fig. 1.4 (Pg. 6 (a)). The amount of visible light from the sun, changes very little from one day to the next; the day to day variations in the quiet ionosphere however suggest that the ultra-violet and X-ray radiation varies considerably.

Apart from these wave radiations, the sun continuously emits a stream of charged particles called the 'solar wind' (Parker 1958). This stream consists of equal numbers of electrons and positive particles (mostly protons) and is electrically neutral as a whole. Its existence was first recognised by Biermann (1951, 1952) and Störmer (1955). Recent satellite observations of interplanetary space show that the quiet-time solar wind has velocities of 300-600km/sec (Gringauz et al., 1961; Wolfe et al., 1966) and densities of 2-20 protons/cm^3 (Coon 1966; Neugebauer and Snyder 1966).

It is believed that viscous interaction between this solar wind and the magnetopause produces large-scale electric fields at high latitudes which could be communicated to lower latitudes (Obayashi and Nishida 1968).

Parker (1958) believes that the solar wind is the hydromagnetic expansion of the solar corona into space, and carries along with it "frozen-in" solar magnetic field lines whose ends remain anchored to the emissive region of the sun.

In the equatorial plane, these magnetic field lines have a radial structure extending out to 2 or 3 solar radii (well beyond the earth), and a curvature induced by solar rotation. Solar magnetic fields exhibit a sector structure (Ness and Wilcox 1966).

1.5 Interaction of solar radiations with the earth's atmosphere

The interaction of solar radiation with the earth's atmosphere manifests itself in various ways.

1. Photochemical reactions - are caused by solar photon absorption and result in the formation of nitric oxide, ozone, and other such complex molecules. Photon absorption sends atmospheric atoms and molecules into excited states, and they emit "airglow" in returning to their ground states.

2. The formation of the ionosphere is a result of the ionisation of elements caused by solar radiations at heights of 60 km and more. The photo-ionisation is chiefly caused by a wide spectrum of solar X-ray and extreme ultraviolet radiation. The basic theory of photoionisation was developed by Chapman (1931 a, b), and assumes that the rate of ion production for a solar zenith angle χ and reduced height $z = \int \frac{dh}{H}$ is given by

$$q(z,\chi) = q_0 \exp(1 - z - e^{-z} \sec\chi)$$

where $q_0 = \frac{\eta I_\infty}{eH}$ is the peak production rate for an overhead sun.

η - ionising efficiency
I_∞ - unattenuated flux at top of atmosphere
e - exponential factor
H - scale height

The formation of different layers - the D-region from 60 km to 90 km, the E-region from 90 km to 140 km, the maximum ionisation in the F-region from 140 km to over 300 km, and the topside with its gradually decreasing electron densities, is associated with the different photoionisation and recombination rates and differing transport effects for the various regions.

It is gradually gaining acceptance that a finite amount of atmospheric ionisation is caused by solar corpuscular radiation even at lower latitudes. This is especially true of higher magnetic latitudes where charged particles enter easily. Within a given energy range, the production function broadly resembles a Chapman function. Some calculations of penetration depths have been given by Bailey (1959), Rees (1963) and Kamiyama (1966).

3. Motions of the neutral and ionised atmosphere are another result of this solar radiation interaction. The lower atmospheric levels absorb solar energy in the form of heat, setting up pressure and thermal gradients over the global surface. This gives rise to neutral wind motions which drag ionisation along. The thermal heating also sets up tidal forces which drive the atmospheric dynamo in the earth's magnetic field, and thereby sets up current systems in the atmosphere. These currents interact with the earth's magnetic field to set up electrodynamic drifts (often called the Hall drift, or the $\vec{E} \times \vec{B}$ drift) which cause the motion of charged particles.

1.6 The Earth's Magnetic Field

The earth has an inherent magnetic field which to a first order approximation, is a dipole field. It is believed to consist of two parts:

1. The "main field" which is caused by the dynamo action of the molten metallic core within the earth (Elsasser 1950) and accounts for 99% of the total field. Its secular variations are slow and stable and change by only a few percent in hundred of years.

2. The "variation field" was once believed to be caused entirely by currents flowing in the ionosphere, but it is now said that there is a significant magnetospheric contribution to it. Only 1% of the earth's mean field is dependent on this, but the transient variations vary rapidly from night to day, with solar cycle epoch, and the state of magnetic activity, and are thus greatly dependent on ionospheric electron densities.

The geomagnetic field can be approximated to the first order by an eccentric dipole field, the geomagnetic axis making an angle of 11° with the geographic axis of the earth. The points at which the field lines actually become normal to the earth's surface are called the earth's dip poles. The geographic latitude and longitude of the magnetic dip poles for the real field, the centred dipole field, and eccentric dipole field are given below (Dessler 1961).

	Northern hemisphere	Southern hemisphere
Actual field	74°N, 259°E	68°S, 144°E
Centred dipoles (Geomagnetic poles)	79°N, 291°E	79°S, 111°E
Eccentric dipole	82°N, 223°E	68°S, 131°E

The coordinates of a place with respect to the theoretically computed dipole which best approximates the earth's magnetic field are defined as geomagnetic coordinates or dipole coordinates. The intersection of the equatorial plane of the dipole with the earth's surface defines the geomagnetic equator. The geomagnetic inclination θ of the magnetic vector is related to the geomagnetic latitude ϕ by the equation

$$\tan \phi = \tfrac{1}{2} \tan \theta$$

The locus of points on the earth's surface along which the vertical component of the actual geomagnetic field is zero is called the magnetic equator or the dip equator. An equation similar to the one above relates the magnetic latitude or dip latitude to the actual magnetic inclination.

The relative displacement of the geographic, geomagnetic and dip equators is shown in Fig. 1.5 (Pg. 12 (a) It is only in the African region that the dip and dipole latitudes differ appreciably. It has been shown (Rastogi 1959) that the

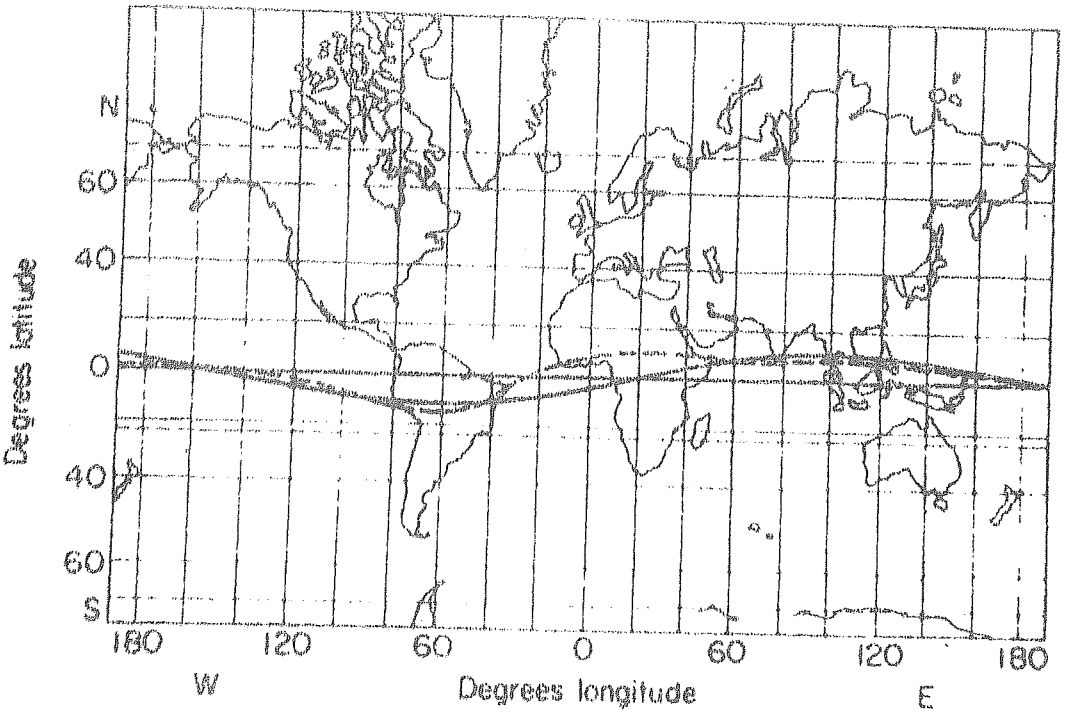


Fig. 1.5 World map showing geographic equator (thin full line), dip equator (broken line) and dipole equator (thick full line).

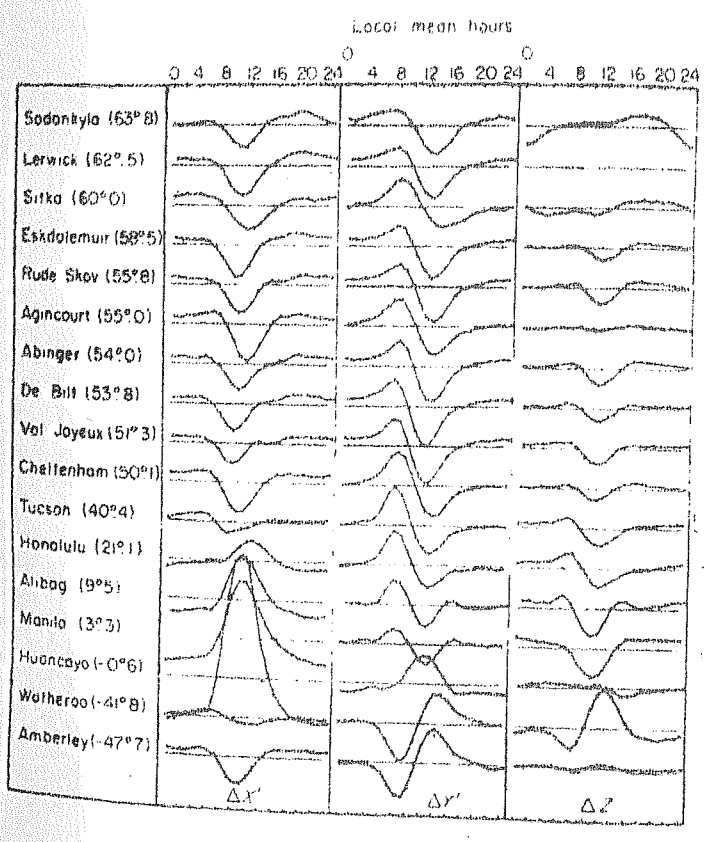


Fig. 1.6 Equinoctial S_q variation in magnetic components X, Y, Z for 1922-1933 (Vestine et al., 1947)

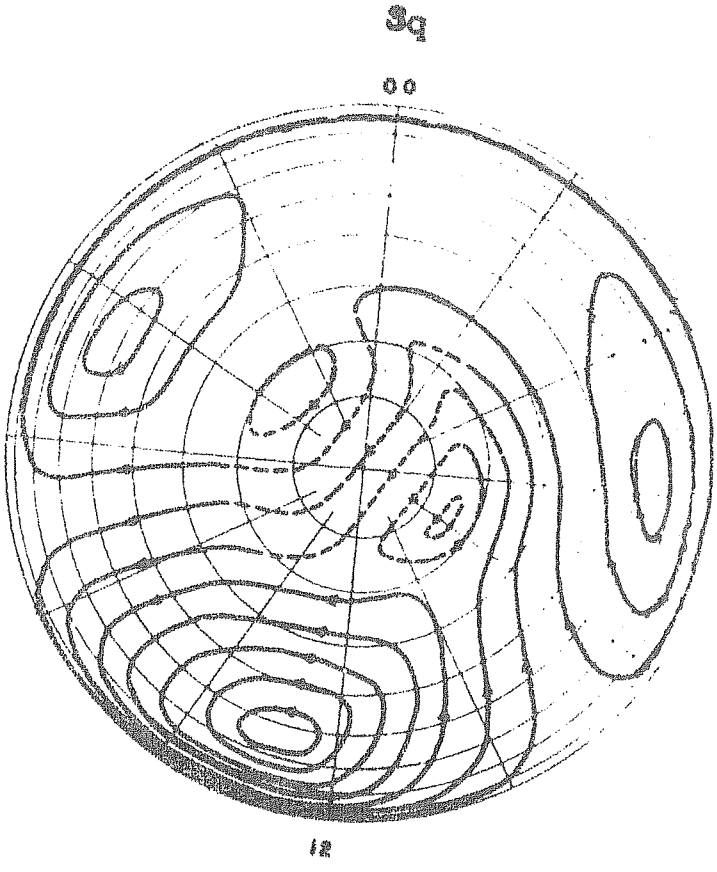


Fig. 1.7 The observed S_q electric current system (based on Vestine et al., 1947)

(Obayashi and Jacobs 1957)

ionospheric F-region behaviour is governed by dip rather than by dipole latitude, and hence the analysis in this Thesis is based on dip as an index of latitude.

The intensity of the dipole field decreases inversely as the cube of the distance from the earth's centre. Most surface anomalies decrease with increasing altitude and at greater distances from the earth, the geomagnetic field almost approaches a dipole field.

The geomagnetic field can be described better in terms of the integral invariants - the three invariants of motion of a charged particle trapped in the earth's magnetic field. These are called the B-L system or the Mc Ilwain system of co-ordinates in which B is the magnitude of local magnetic induction, and L is a "shell parameter" depending on both B and I (the longitudinal invariant). Such a coordinate system has been described by Mc Ilwain (1961).

1.7 The quiet day variations of the geomagnetic field and the dynamo theory.

The Sq or solar quiet day variations of the magnetic elements $\triangle X$, $\triangle Y$, and $\triangle Z$ for equinox at the various latitudes is shown in Fig. 1.6 (Pg. 12 (a)) after Vestine et al., (1947).

Such observations of the earth's magnetic field have been made since before 1600, and Graham in 1722 pointed out the existence of daily variations in the geomagnetic field.)

In 1882, Balfour Stewart suggested the existence of an atmospheric dynamo caused by solar heating to explain these small regular daily variations of the geomagnetic field. Today we know that the moon exerts tidal pulls on the atmosphere with the same dynamo effect. The quiet-time overhead current system has thus a solar component S_q and a much smaller lunar component L. The dynamo theory was first formulated mathematically by Schuster (1908), and by Chapman(1919) and developed gradually by a number of workers. (Baker 1953; Fejer 1953; Kato 1956; Macda 1955).

From the recent progress in our knowledge of the earth's atmosphere, it is known that the maximum conductivity of the ionosphere is found at a height of 100 km, and the dynamo currents flow here on the surface of a sphere concentric with the earth. The S_q current system for the northern hemisphere, based on Vestine's analysis (1947) is shown in Fig. 1.7 (:Pg.12(a)) after Obayashi and Jacobs (1957). The greater concentration of current in the dayside with a marked density in the equatorial region (representing the equatorial electrojet) is seen clearly from the figure. The sparser lines in the nightside are an indication of very small current intensities; the twin vortices at the poles may be noted.

It can be seen how the following features of the geomagnetic field variations of Fig. 1.6 (Pg. 12 (a)) fit in with the Sq current system.

1. The transition from daytime positive to negative variations of Δ X occurs around $\pm 40^{\circ}$ geomagnetic latitude, at the foci of the dynamo current systems. At lower latitudes, the positive Δ X variations correspond to eastward currents while at latitudes above $\pm 40^{\circ}$, the negative Δ X corresponds to westward currents.

2. At night the variation of the geomagnetic field parameters is less than by day, corresponding to reduced nocturnal currents.

3. There is a phase reversal in ΔY and ΔZ (not Δ X) across the equator, corresponding to reversal in the current directions.

4. There is abnormally large increase of ΔX in the equatorial regions. This is caused by the equatorial electrojet current, described below.

1.8 The equatorial electrojet

The abnormally large variation of S_q(H) variation at an equatorial station was first discovered by McNish at Huancayo in 1937, and was interpreted by him as due to a

strong eastward current flowing at ionospheric heights in the daytime. Egedal (1947, 1948) showed that this enhancement of $\triangle H$ is confined within a belt of $\pm 3^0$ about the magnetic equator. The current was named the equatorial electrojet by Chapman (1951). Longitudinal variations in the electrojet were suggested by Rastogi (1962), that it is strongest in the American Zone, and weakest in the Indian Zone. The direct detection of the equatorial electrojet has been made by rocket borne magnetometers (Singer et al., 1952; Maynard and Cahill 1965 a, b; Sastry 1968) and these have confirmed the longitudinal asymmetry mentioned above. Davis et al., (1967) found that at night there is a small westward electrojet, and this was confirmed by Balsley (1966).

The cause of the equatorial electrojet is as follows: Near the magnetic equator, the Hall current (due to the interaction of the East-West electrostatic field, and the North - South magnetic field) is inhibited giving rise to a vertical polarisation field due to the special property of the lines of force here being perfectly horizontal (Baker and Martyn 1953). This gives rise to an additional conductivity in the same direction as the normal Pedersen conductivity (σ_1). The effective conductivity is known as the Cowling conductivity σ_3, and is given by

$$\sigma_3 = \sigma_1 + \frac{\sigma_2^2}{\sigma_1} = \sigma_1 \left[1 + \left(\frac{\sigma_2}{\sigma_1} \right)^2 \right]$$

$$\approx \left(\frac{\sigma_2}{\sigma_1} \right)^2 . \sigma_1$$

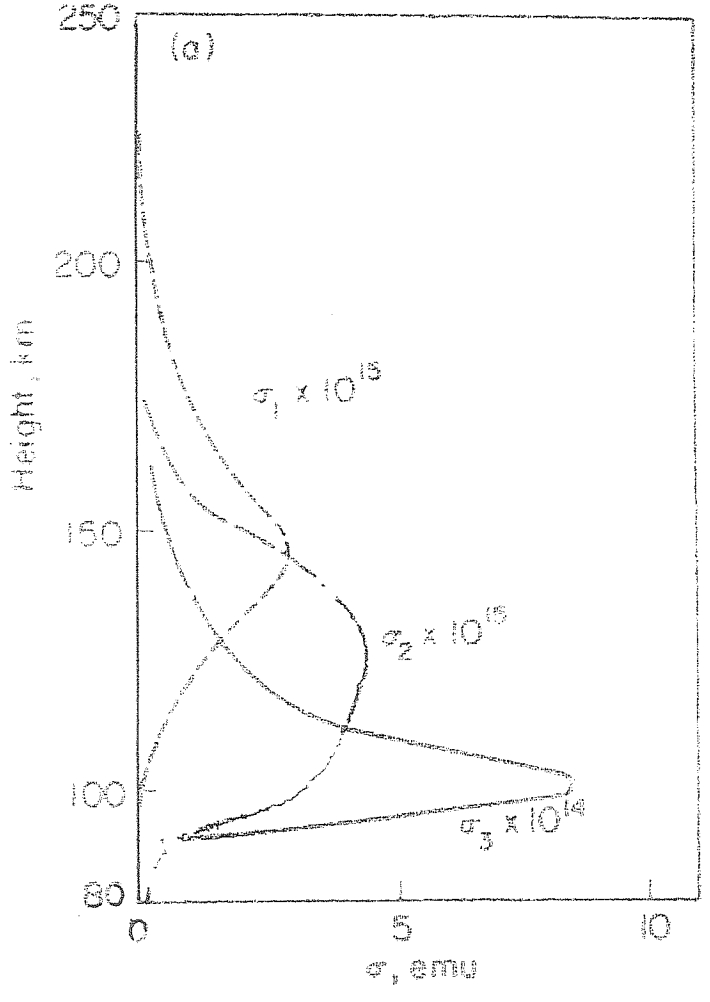


Fig. 1.8 (a) Height-variation of conductivities σ_1 (Pedersen), σ_2 (Hall), σ_3 (Cowling) (after Chapman and Raja Rao 1965)

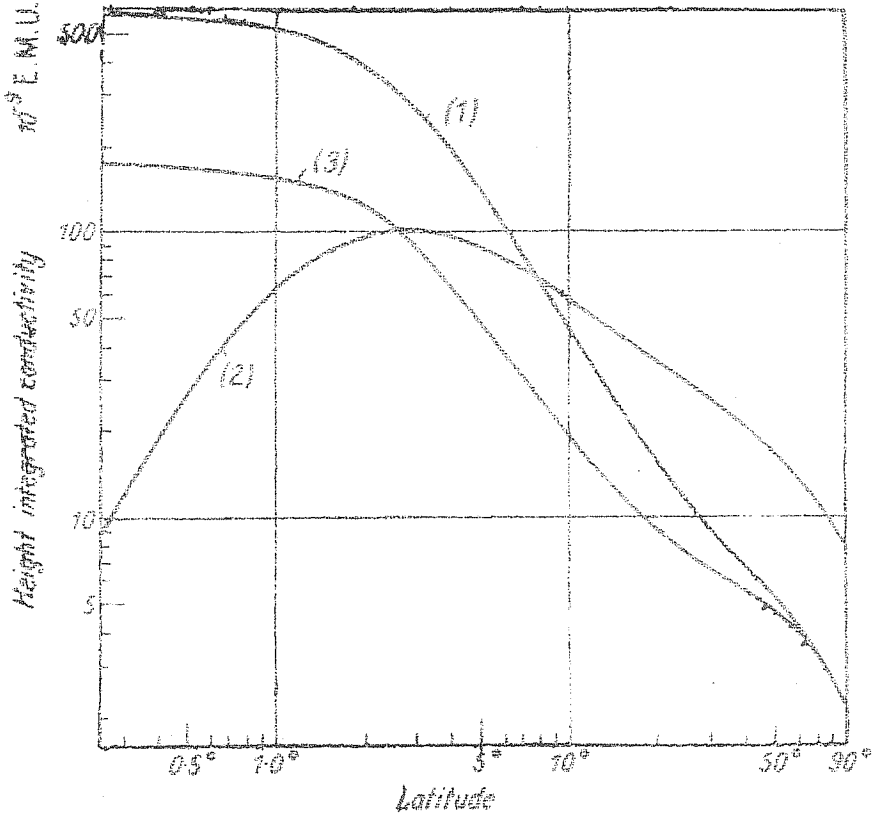


Fig. 1.8 (b) Latitude-variation of height-integrated conductivities (1) $\int \sigma_{xx}\, dz$ (2) $\int \sigma_{xy}\, dz$ (3) $\sigma_{yy}\, dz$. (Fejer 1953)

16(a)

The variations of σ_1, σ_2 and σ_3 with altitude and latitude are shown in Fig. 1.8 (a) and (b) (Pg. 16(a). In the 100 km region σ_2 is about 20 times σ_1, and $(\frac{\sigma_2}{\sigma_1})^2$ is about 400 times σ_1 . This explains how in the vicinity of the dip equator, the ionospheric conductivity is very large as compared to other latitudes.

1.9 Geomagnetic field parameters at earth's surface

World-wide contours of F (the total intensity of the earth's field in gauss), D(declination in degrees) and Z (vertical intensity in gauss) at the surface of the earth, are given in Figs. 1.9, 1.10, and 1.11 (Pg. 17 (a)). It is seen that there is a good amount of longitudinal variation in the parameters, and the largest differences exist between the 75°W (American) and 75° E (the Australasian) Zones.

These differences are summarised here in tabular form and have been the cause for the selection of the two zones chosen in this thesis for the study of storm-time F_2 effects.

Geomagnetic field characteristics

	Asian zone	American zone
1.	At the dip equator, the total field intensity is around 0.40 gauss	At the dip equator, the total field intensity is only around 0.26 gauss.

17(a)

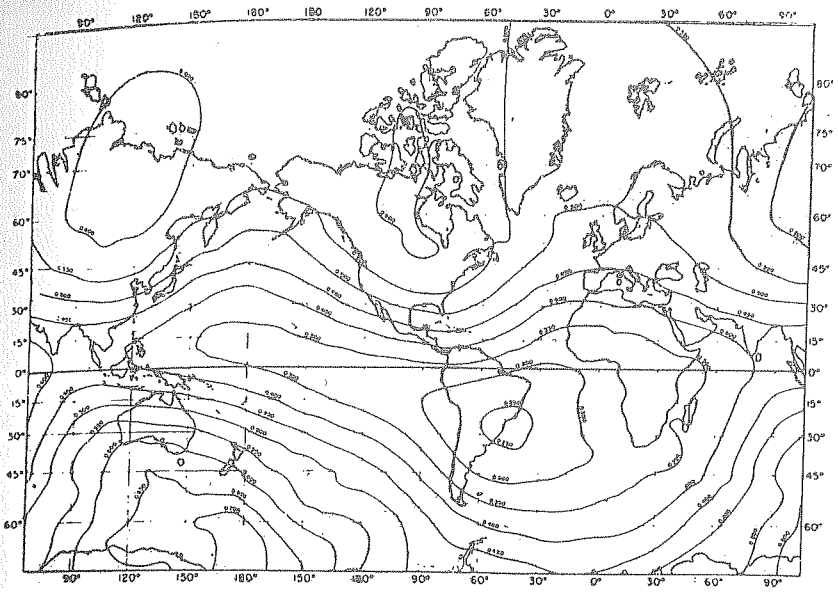


Fig. 1.9

Total intensity F (in gauss) of earth's magnetic field (Hand–book of Geophysics; U.S. Air Force 1960)

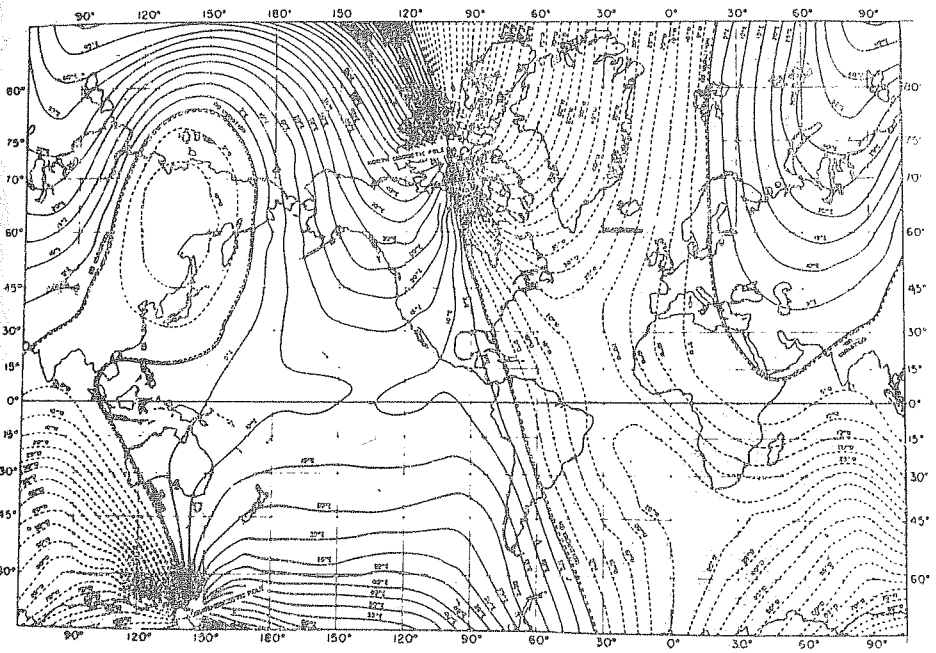


Fig.1.10

Declination D (in degrees) of earth's magnetic field. Full lines show easterly (positive) variation, dashed lines westerly (negative) variation (Hand–book of Geophysics; U.S. Air Force).

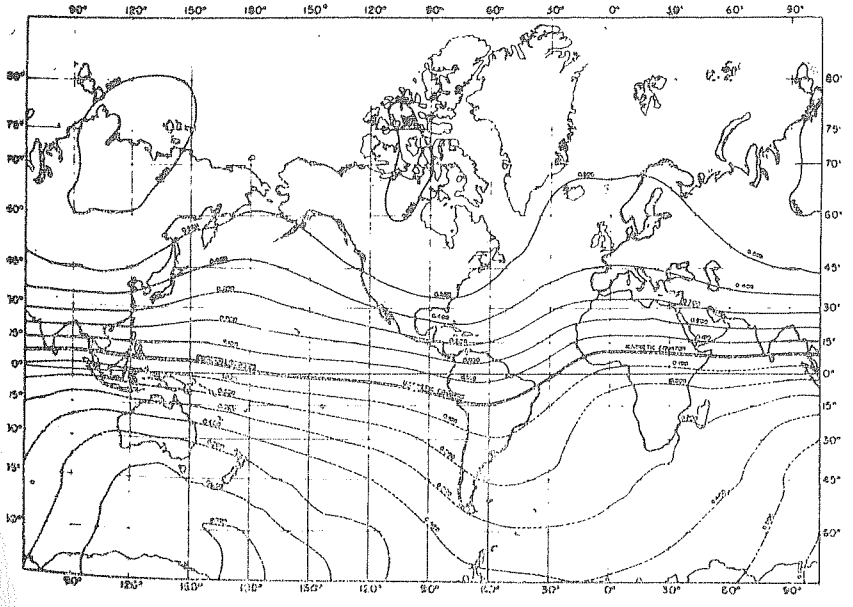


Fig.1.11

Vertical intensity Z (in gauss) of earth's magnetic field. Full lines indicate positive dip, dashed lines negative dip, (Hand–book of Geophysics; U.S. Air Force 1960).

	Asian zone	American zone
2.	The dip equator is almost parallel to the geographic equator, and lies about 10 geographic degrees north of it. The isodip lines are all parallel to the geographic equator.	The dip equator lies almost 15 geographic degrees south of the geographic equator. The isodip lines are non-parallel to the geographic equator and are deeply convex southwards in the South American zone.
3.	In both northern and southern hemispheres, the geographic and magnetic latitudes of a station are not greatly different.	In the northern hemisphere the geographic and magnetic latitudes of a station are not very different. In the southern hemisphere, isodip lines curve far south, so a station with a very high geographic latitude has relatively a small dip latitude; hence geophysical features subject to geographic and geomagnetic causes are vastly different here.
4.	In the East zone, most stations lie in a zone of no variation of declination, or at the most within a range of 10° change of declination.	In this zone, there is a sharp gradient of declination right from the north to south, the variation ranging upto 35° in some areas.
5.	The south magnetic pole lies south of Australia	The north magnetic pole lies in north Canada.

The differing geo-field intensities could be expected to affect the dumping of charged particles from the radiation belts during magnetic disturbances. The mirror points of a charged particle gyrating along the field lines of the earth are dependent on the relationship -

$$\mu = \frac{\frac{1}{2} m v_{\perp}^2}{B} = \frac{\frac{1}{2} m v^2 \sin^2 \alpha}{B} = \text{constant}$$

Where

μ is the first adiabatic invariant, v the velocity of the particle, α is its pitch angle and B the magnetic field intensity it finds itself in.

At a point where $\sin \alpha = 1$, the particle turns around and starts moving back along the field line; this point of "reflection" is called the mirror-point and the value of B here is defined as B_m. The value of B_m has to be constant for a given charged particle with a given pitch angle. In the American zone where B has a smaller value than in the Asian zone, the charged particle clearly has to approach nearer the earth to obtain $B = B_m$. This increases the possibility of its coming lower down and being lost in the atmosphere, thereby creating secondary ionisation observable in the lower regions. Satellite studies have indeed shown the influx of such ionisation over the South American anomaly region.

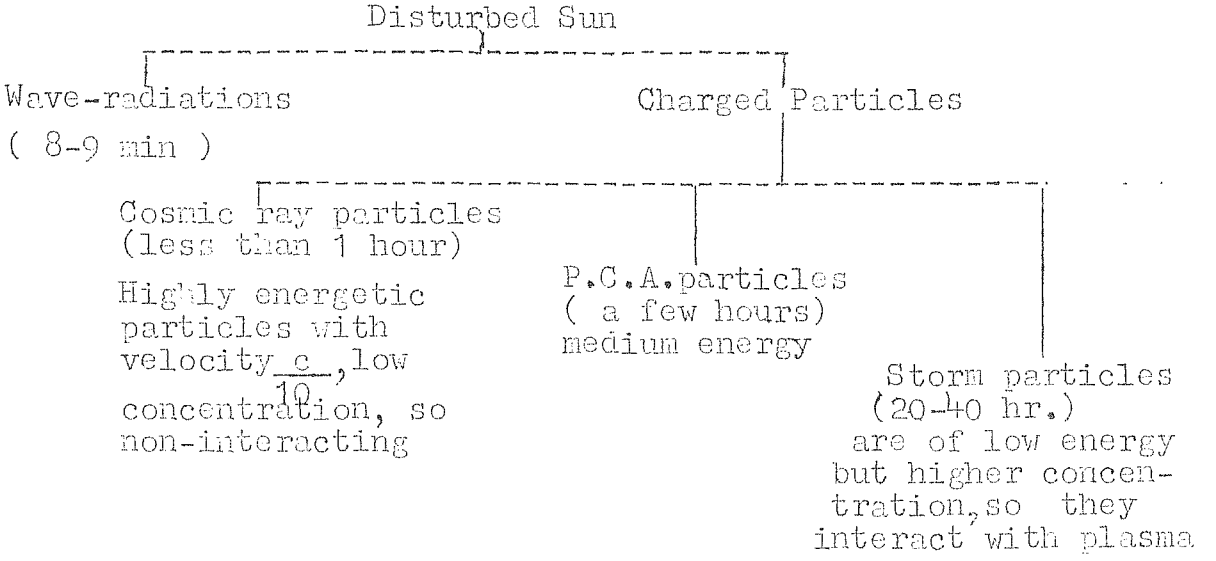
In the East zone, with its higher geomagnetic field intensity, charged particles would mirror at greater heights and would contribute little to observable ionisation lower down.

B - THE DISTURBED SUN-EARTH ENVIRONMENT

1.10 Disturbed Solar Emissions

From time to time the sun goes into a state of enhanced activity, and there is a great increase in its electromagnetic and corpuscular radiation, giving rise to disturbances in the earth's upper atmosphere. At such times, there are distortions of the normal quiet-time features.

The types of radiations emitted from the Disturbed sun with their time sequences are shown schematically below.



The wave-radiations manifest themselves almost simultaneously on earth with the observation of enhanced solar features and include S.I.D. effects due to increased X-ray, ultra-violet, visible and radio-wave radiations.

Corpuscular radiations can be emitted as streams or clouds. Streams are believed to be continuously emitted from unipolar magnetic regions (U.M. regions) on the solar surface and exhibit a 27-day recurrence pattern. Clouds are said to be sporadic and violent eruptions from bipolar magnetic regions called centres of activity (C.A.), and their intensity and frequency shows a dependence on the 11-year solar cycle.

The mechanisms suggested for the emission of these radiations all depend in some way or the other on the magnetic field of the solar region concerned. A cloud or stream of storm particles, which breaks away, carries away a "frozen-in" portion of the solar magnetic field in the form of a "tongue" (Gold 1959), and travels with a velocity of 1000-2000 km/sec. Satellite studies (Coleman et al., 1960; Fan et al., 1960) have traced out the progress of such storm plasma and the changes it causes in interplanetary space.

The storm plasma sweeps the inter-planetary gas ahead of it in the form of a "shock front" which manifests its arrival at the magnetopause as a sudden commencement (s.c.) or a sudden impulse (s.i.).

Once the particles arrive here they are affected by the geomagnetic field to

1. be deflected away from earth
2. or be trapped into the radiation belts from where they can slowly leak into the auroral atmosphere
3. or penetrate into the earth's atmosphere along the polar field lines or through the magnetospheric tail.

1.11 The disturbed geomagnetic field

The magnetograms of H at several latitudes during disturbed conditions are shown in Fig. 1.12 (Pg. 22 (a)). When the sharp change at the commencement of the storm is not visible on the record, it is called a g.c. or a gradual commencement storm. The initial phase, main phase, and recovery phase are indicated on the curves; it should be mentioned that the vertical scale for the auroral zone (ii)has been reduced by a factor of ten.

The disturbed field D is believed to be composed of two components (1) the D_{st} which ~~which~~ is dependent on universal time and independent of longitude and (2) the DS which is a function of local time. The current systems associated with the DS is shown in Fig. 1.13 (Pg. 22 (a)) after Obayashi and Jacobs (1957).

22(a)

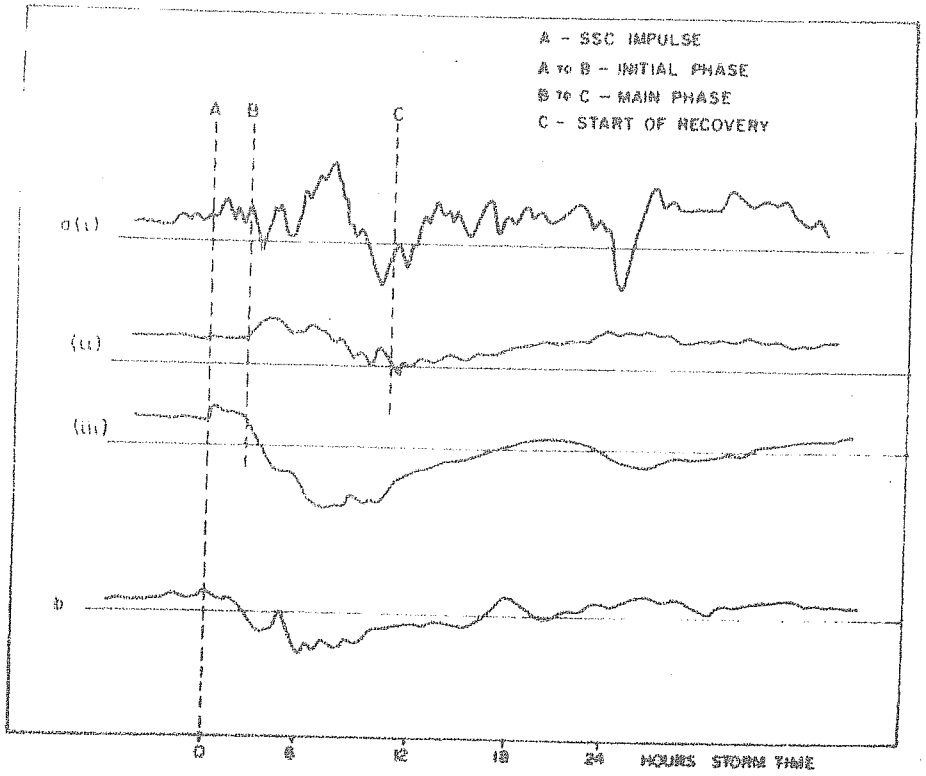


Fig. 1.12 Storm - time H variations of standard magnetograms (Paghis 1965) (a) s.c. storm at (i) polar cap (ii) near auroral zone (ii) at low latitude (b) g.c. storm at low latitude

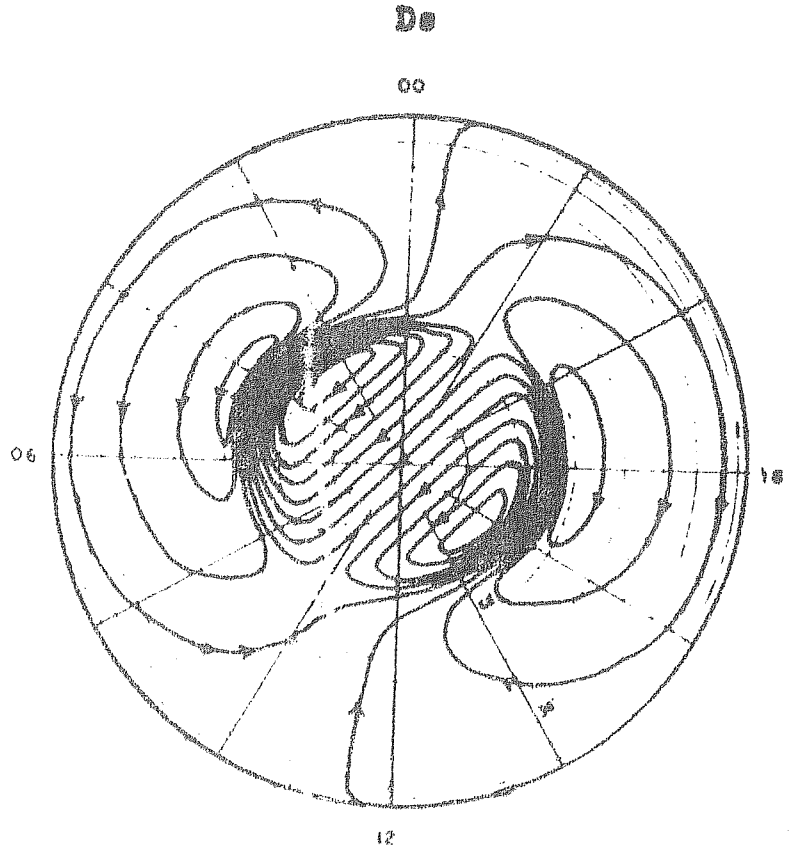


Fig. 1.13 The observed Ds electric current system (based on Vestine et al., 1947).
(Obayashi and Jacobs 1957)

The s.c. as has been mentioned earlier, is due to the arrival at the magnetopause of the shock front, and manifests itself as a sudden sharp change in magnetograms. Chapman (1963 b) classified the disturbance field as arising from three physical processes.

$$D = DCF + DR + DP$$

The initial phase is believed to be caused by the compression of the magnetospheric cavity by the DCF disturbance corpuscular flux). The main phase is associated with westward ring currents in the magnetosphere located at $4-6\ R_e$. which form the DR part of it. The DR part is itself formed of two parts - the DR 1 which is most intense in great storms and often disappears within a day of the storm, and the DR_2 which is a longer-lived feature, and is more frequent in weak storms.

The DP part (disturbance polar) is due to currents flowing in the earth's ionosphere and is most concentrated in the polar regions. It manifests itself as the DP_1 (the auroral electrojet current system) and the DP_2 (the twin current vortices).

The DP_1 or the Auroral electrojet is a westward current located around $65^\circ - 70^\circ$. It is strongly concentrated along the nightside auroral zone as can be seen from Fig. 1.14

(Pg. 23 (a)

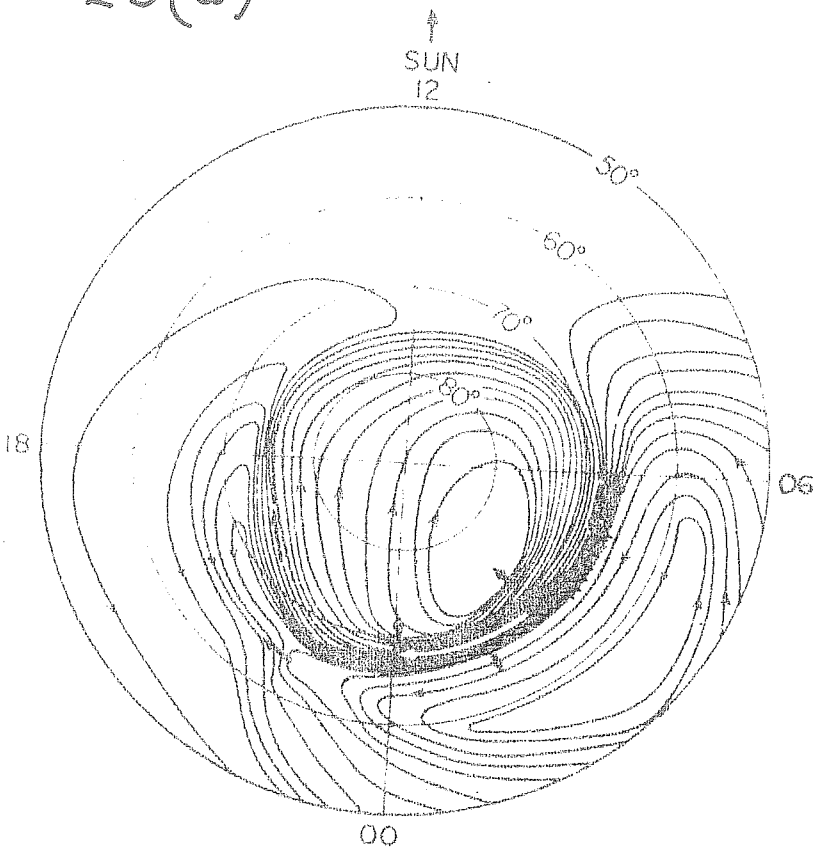


Fig. 1.14 Model proposed for DP-1 current system (Akasofu et al., 1965).

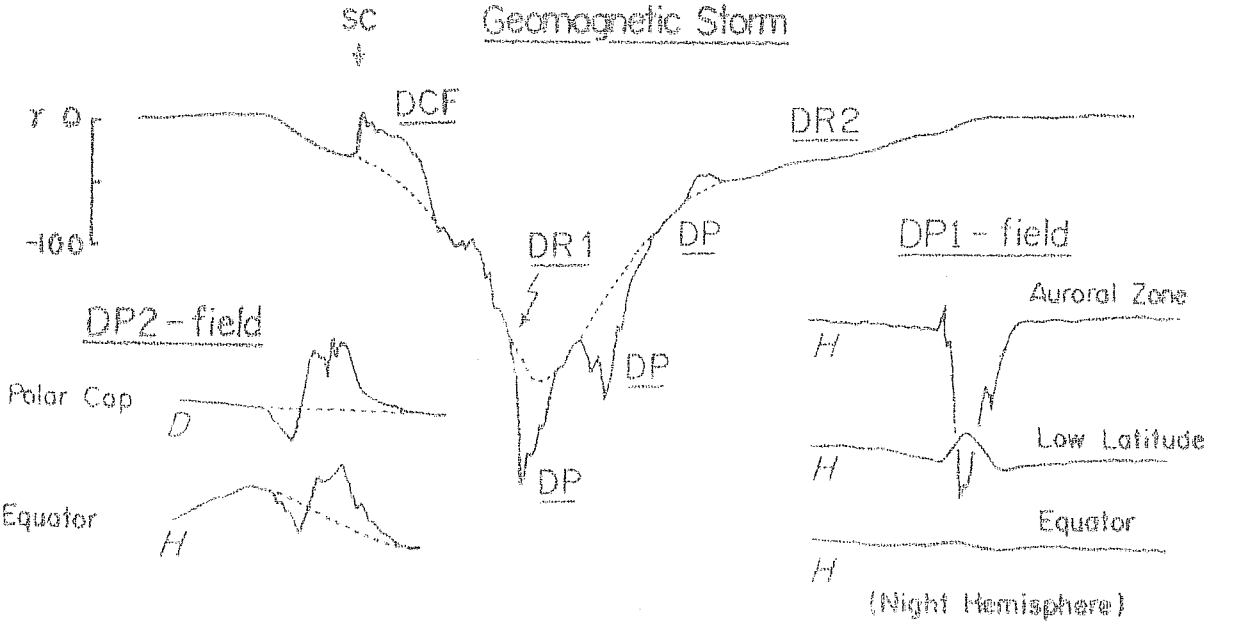


Fig. 1.15 H variations caused by DCF, DR, and DP during a geomagnetic storm (Obayashi 1967).

(after Akasofu et al., 1965) and the return currents encircle the polar cap and low latitudes. The DP_1 can occur during quiet conditions, but it is more intense and frequent during storms, and manifests itself as bays or negative excursions in magnetic records at high latitudes. Occasionally (particularly in the afternoon) the direction of the auroral electrojet is eastward, in which case it returns along the equator as a westward current.

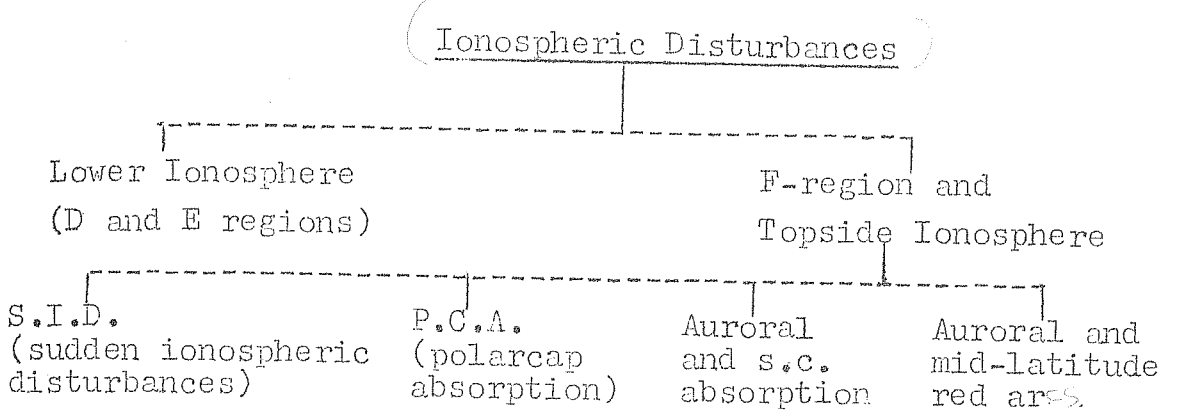
There is another current system at high latitudes known as DP-2 (Nishida et al., 1965). This is a twin-vortex system centred along the morning - evening meridian, and the return currents extend to low latitudes. A weak form of DP-2 exists even at quiet times, and is known as Sq^p.

The occurrence of DCF, DRI, DR2, and DP on a schematic magnetogram are shown in Fig. 1.15(Pg. 23 (a)) after Obayashi (1967).

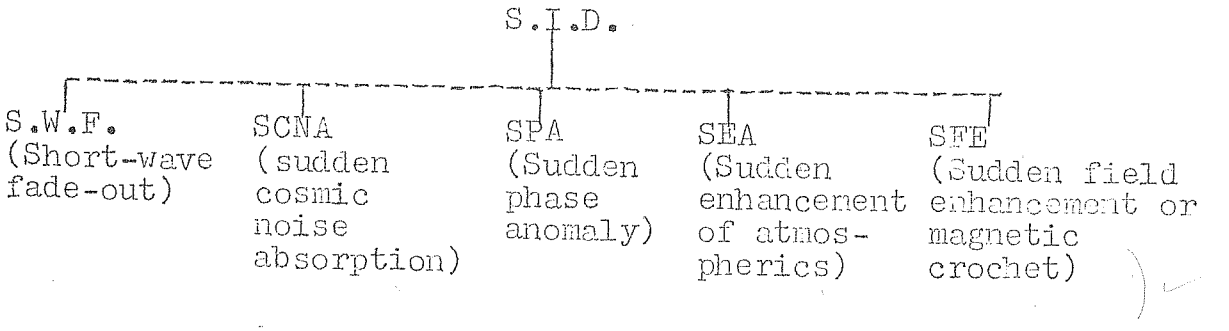
1.12 Disturbance effects in the Ionosphere

Magnetospheric changes brought about by storm plasma manifest themselves as disturbances in the geomagnetic field and the ionosphere through magnetosphere-ionosphere interactions. Aspects of these interactions are dealt with by Obayashi (1967), Axford and Hines (1961), Parker (1962), Piddington (1960, 1964) and Dungey(1963). Disturbances in the ionosphere can be classified under two broad headings

those in the lower ionosphere (D and E regions) and those in the F-region. A good review of ionospheric disturbances is given by Reid (1967). These disturbances can be further sub-divided as



S.I.D.'s are associated with the disturbed wave-radiations and generally manifest themselves in the sunlit hemisphere in these forms.



Ionospheric F-region disturbances

The F-region is one of the most sensitive indicators of geomagnetic storms, and is the subject of the present investigation. Large changes in electron density follow a storm, their dependence on latitude being treated in detail in the chapters which follow. Much work has been done on F-region storms but as yet there is no satisfactory explanation of the major features,

1.13 The indices of geomagnetic activity

The degree of geomagnetic disturbance is described by indices which are derived from the regular measurements of the field components made all over the earth. There are several types of indices, but they are all measures of the mean rate of change of the magnetic field.

The magnetic character figure C has been in use since 1884. Depending on whether the daily variation of the magnetogram is quiet, moderately disturbed, or highly disturbed, it assumes the values 0, 1, 2.

The K-indices are three-hourly indices on a quasi-logarithmic scale varying from 0 to 9 and are computed to the nearest 1/3 of a unit. They depend on the latitude of the magnetic observatory - a low latitude station has K = 9 for 300 gammas while an auroral latitude puts K = 9 for a change of 2500 gammas or more. Daily K values are obtained from the sum of eight 3-hourly K values. Bartels (1957) has developed a "planetary" series of activity indices obtained from mean indices of twelve observatories located in the higher mid-latitudes (47° to 63° geomagnetic latitude). These can be the C_p or the K_p indices depending on whether they are derived from C or K. The quasi-logarithmic K_p scale can be converted into a linear Ap scale.

Satellite observations have shown marked correlation between Kp and (1) solar wind velocities and densities in interplanetary space (2) atmospheric temperatures during storms, and many such geophysical features.

CHAPTER - II

THE MORPHOLOGY OF THE QUIET F-REGION

2.1 Introduction

The F-region of the ionosphere can be defined as the part of the ionosphere lying above 140 km. The lower limit is fairly well-defined, but the upper limit is greatly dependent on latitude, season, and solar cycle epoch. The upper boundary may be taken as the level where the light ions He^+ and H^+ replace O^+ as the dominant ion i.e. at about 600- 1000 km. By day the F-region bifurcates into two layers - the F_1 and the F_2 layers - and by night unites to form a single layer again.

The F_1 region can be considered to exist between 140 km and 200 km where the predominant ions are NO^+ and O_2^+. The electron concentration is typically of the order of (2.5×10^5) electrons/cm^3 at noon during sunspot minimum, (4.0×10^5) electrons/cm^3 during sunspot maximum, and exhibits large diurnal variations. The F_1 region was previously believed to show a simple solar zenith angle dependence, but gradually this was disproved. Rastogi (1958) showed that while this was true of the high latitudes, stations at middle and equatorial latitudes showed equinoctical maxima; also that markedly in high sunspot years, the latitudinal variation of f_0F_1 shows a trough about the equator, and is hence subject to some form of geomagnetic control.

The F_2 region exists above 200 km and the composition here is mainly O^+ and to a smaller extent H^+ (Johnson et al., 1958; Istonin 1960; Poloskov 1960). The reason why a second ionisation peak is formed at the F_2 region although the peak production occurs in the F_1 region, is that the recombination rate falls off more rapidly with altitude than does the ionisation rate. Ultimately, downward diffusion of ions becomes faster than either ionisation or recombination, and causes ionisation to decrease above the F_2 peak.

The behaviour of $h_{max}F_2$, the height of peak F_2 ionisation is quite complicated. In Fig. 2.1 (Thomas, 1959) (Pg. 29 (a)) is shown the latitude - dependence of h_mF_2 averaged at noon and midnight equinox for two epochs of the solar cycle. In general at high latitudes, $h_{max}F_2$ is higher at night than by day, while the reverse is seen at the equator. There is a general trend for $h_{max}F_2$ to be greater in summer than in winter, and also to increase with solar activity. The solar cycle and seasonal variations of $h_{max}F_2$ for equatorial stations are dealt with in detail in Section 2.7.

The F-region reveals itself in diverse forms and shapes on ionograms obtained from ionosondes. One of these forms shows a diffuse character called spread-F which is attributed to scattering by irregularities of ionisation imbedded in the surrounding region. This feature has marked latitudinal and diurnal variations (Shimazaki 1959) . In low-latitudes

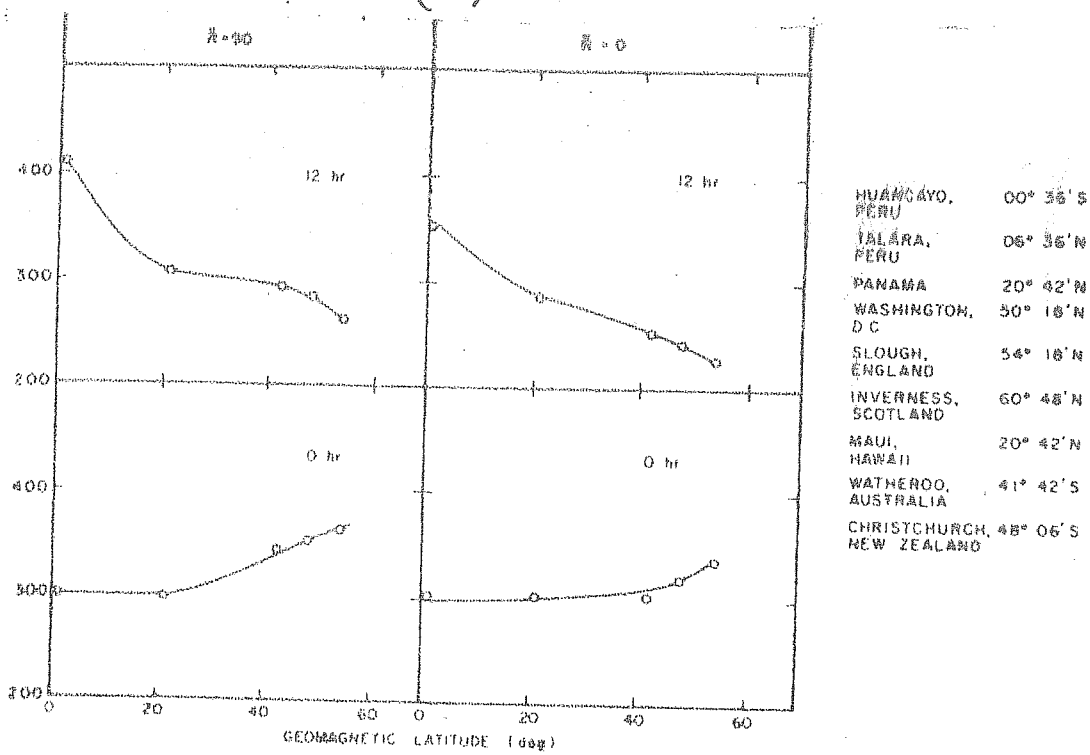


Fig.2.1 Equinoctial variation of $h_{max}F_2$ with geomagnetic latitude for high and low sunspot, day and night(Hanson 1961)

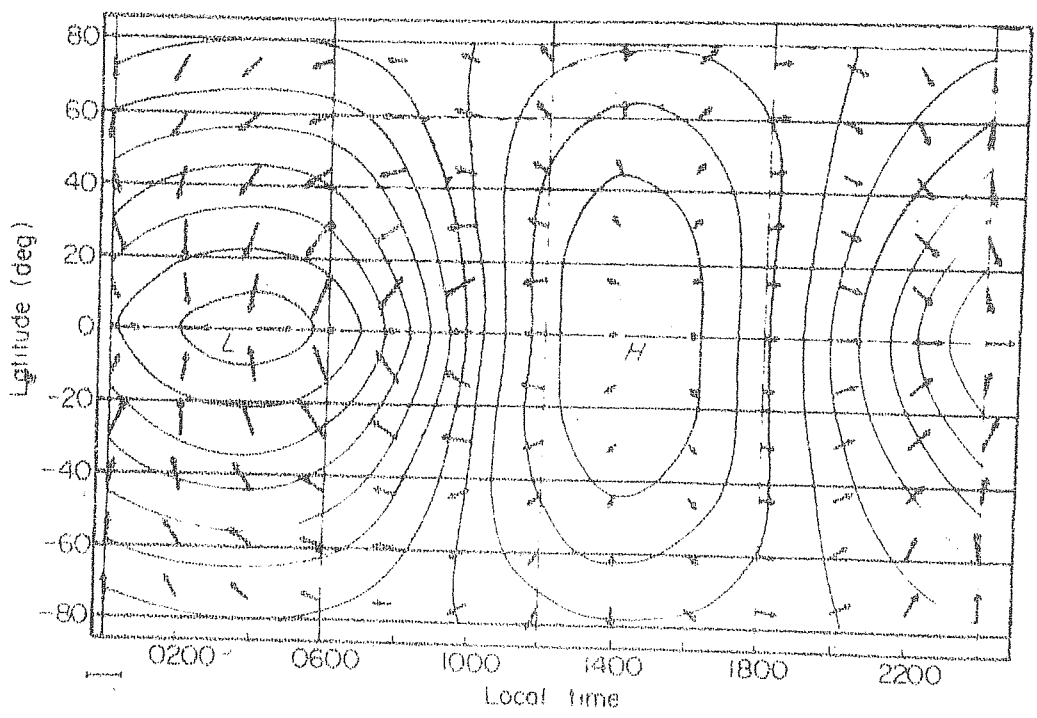


Fig.2.2 Computed wind vectors at 300km. The bar at bottom left represents a wind vector of 200m/sec. (Geisler 1967b)

sometimes an additional stratification called the $F_{1.5}$ layer appears (Kasuya, 1957; Kotadia, 1963). Often irregularities with quasi-periodicities of 15 min to 1 hour show up on ionograms as travelling disturbances (Heisler 1958; Munro 1958). Most observations show these to move downwards in the F-region, but recently Rastogi (1970) has observed upward-travelling kinks at Indian equatorial stations, which are in a sense, direct evidence of the vertical $\vec{E} \times \vec{B}$ drift.

2.2 Chemistry of the F-region

The F-region like the other ionospheric regions experiences production and loss of ionisation. In addition, it is controlled to a great extent by transport processes arising from various causes, and these are discussed in the next section. Ionisation in the F-region is caused by the spectrum of solar radiation lying between 200 A° and 911 A°, chiefly by the He I (584 A°) and He II (304 A°) lines (Hinteregger et al., 1960). The photo-electrons are released with relatively high energy which they share with neighbouring electrons. Consequently, electron temperatures can be several hundred degrees higher than the ion temperatures in the daytime (Hanson and Johnson 1960).

For wave-lengths outside this range, the absorption cross-section is too small, and the radiation penetrates to levels below the F-region. The He II (304 A°)

emission has a flux density of about $6 \times 10^9/cm^2$-sec and varies with solar activity. Atomic oxygen is photoionised thus

$$O + h\nu \longrightarrow O^+ + e$$

The electrons formed, recombine directly with atomic ions only at heights above the F_2 peak. Below this, atomic ions first react with neutral molecules to form molecular ions, and these latter recombine with electrons dissociatively.

(1)
$$O^+ + O_2 \longrightarrow O_2^+ + O \quad (\beta = 2 \times 10^{-11}\ cm^3/sec)$$
$$O^+ + N_2 \longrightarrow NO^+ + N \quad (\beta = 1 \times 10^{-12} cm^3/sec)$$

Dissociative recombination takes place as follows:

(2)
$$O_2^+ + e \xrightarrow{2.2 \times 10^{-2}\left(\frac{300}{T}\right)} O^* + O^{**} \quad (\alpha = 2 \times 10^{-8} cm^3/sec)$$
$$NO^+ + e \xrightarrow{5 \times 10^{-7}\left(\frac{300}{T}\right)} N^* + O^* \quad (\alpha = 5 \times 10^{-9} cm^3/sec)$$

The reaction rates for all these are indicated against the equations (Yonezawa and Takahashi, 1960). The excited atoms in returning to their ground-states, emit airglow. The reaction rate of the formation of molecular ions (1) can be expressed as:

$$\frac{dn}{dt}\ (O+) \longrightarrow - K_1\, n\,(O^+)\, n\,(XY)$$

where K_1 - constant rate coefficient

$n(XY)$ - density of neutral diatomic molecule

The reaction rate of electron loss (2) can be expressed as

$$\frac{dN}{dt} = - K_2\, N\, n\,(XY^+)$$

where K_2 - constant rate coefficient

N - electron density

$n(XY^+)$ - density of positive diatomic ion.

$K_1 n\,(XY)$ is effectively the attachment coefficient β and K_2 is effectively the recombination coefficient α.

The net loss rate is $L\,(N) = \dfrac{\beta \alpha N^2}{\beta + \alpha N}$

(Ratcliffe, 1956 a)

From the above relation

If $\beta >> \alpha N$ (as in the F_1 region), $L\,(N) = \alpha N^2$

If $\beta << \alpha N$ (as in the F_2 region), $L\,(N) = \beta N$

This change-over from a quadratic loss to a linear loss occurs at a transition level where

$$\alpha N = \beta$$

It lies at about 160 - 200 km, and happens to coincide with the level at which the production rate 'q' is largest. Ratcliffe (1956 a) showed that these features caused the splitting of the F-region into F_1 and F_2 layers.

Other processes in the F-region have been suggested such as $N_2^+ + O \longrightarrow NO^+ + N$ (Norton et al., 1962).

The rate reaction for

$$N_2^+ + e \longrightarrow N^* + N^{**} \text{ is } \alpha = 2 \times 10^{-6} \text{ cm}^3/\text{sec}.$$

This is believed to be too rapid for ionisation to be observed (Rishbeth 1962).

Changes in atmospheric temperature are believed to affect these reaction rates considerably (Schneltekopf 1967, Yonezawa, 1963; Matuura 1963; Thomas and Norton, 1966; Paulson, 1964). Moreover, the reaction rates given above are all laboratory measurements at around 300°K, whereas temperatures in the F-region are over 1000°K.

2.3 Dynamics of the F-region

The continuity equation for the electron density in the F-region

$$\frac{\partial N}{\partial t} = Q - L - \text{div} \left(\overrightarrow{NV} \right),$$

contains a transport term div $(\overrightarrow{NV})$ which is believed to be

the main cause of the non-Chapman like behaviour shown by the F_2 layer. This term can be expanded into:

$$\text{div } (NV) = \text{div } \left[N \left(\overrightarrow{V_{EM}} + \overrightarrow{V_T} + \overrightarrow{V_D} \right) \right]$$

V_{EM} - movement caused by electromagnetic forces

V_T - movement caused by temperature changes

V_D - movement by ambipolar or plasma diffusion

This mass transport is particularly important at heights above 300 km where the neutral density is smaller, and the effective collision frequency is ν_{ei}, that between electrons and ions. Chapman (1956) estimated ν_{ei} as:

$$\nu_{ei} = \left[34 + 4.18 \log_{10} (T^3/N_e) \right] N_e T^{-3/2}$$

and Martyn (1959) gave the value of ν_{ei} to be 900/sec for the F_2 peak.

The F-region is electrically neutral, and ions and electrons essentially diffuse together (ambipolar diffusion). Except at the equator where the field inclination is such that horizontal movements cannot be neglected, it is assumed that it is only the vertical movements which are important for the transport term and

$$\text{div } (NV) = \frac{\partial}{\partial h} (NW)$$

where W - vertical velocity of ions and electrons.

These are obtained from the equations of motion for electrons and ions (Dougherty, 1961). In recent years there has been a growing emphasis on the part played by neutral winds in exerting ion-drag, and an equation of motion for neutral air too is required (Kohl and King, 1967). Each of these processes is temperature - dependent, and a heat balance or thermal continuity equation is involved too. Thus the complete dynamics of the F-region is obtained by the solution of a set of several equations, which is a very complicated procedure.

In a greatly simplified way

$$V_{EN\ drift} = \frac{E}{B} \cos I$$

$$V_{ion\text{-}drag} = - \frac{u.B}{B} \sin I$$

and

$$V_{ambi\text{-}polar\ diffusion} = -D_a \sin^2 I \left(\frac{1}{N} \frac{\partial N}{\partial z} + \frac{1}{T} \frac{\partial T}{\partial z} + \frac{1}{2H} \right)$$

Where

D_a = ambipolar diffusion coefficient

I - dip angle

T - neutral temperature

H - scale height

u - neutral gas velocity

B - total geomagnetic field

E - East-west component of electric-field

4324.

2.4 Thermospheric wind effects in the F-region

The effect of thermospheric neutral winds on the F-region is believed to be of enough importance to merit the attention of several workers [Johnson 1964; King-Hele 1964; Hines, 1965] G.A.M. King (1964) suggested that the seasonal anomaly of the F-region was caused by a wind system which transported neutral air from the summer hemisphere to the winter hemisphere. King and Kohl (1965) have shown that neutral air pressure gradients at F-layer heights will produce important atmospheric winds.

The driving force for these worldwide thermospheric wind systems are the horizontal pressure gradients around the diurnal bulge caused by the daily temperature variations. The diurnal bulge is the daytime expansion of the atmosphere and is centred in low latitudes at around 1400 hr local time. The highest temperatures, and therefore the highest atmospheric densities, occur near 1400 L.M.T., and the lowest pressures occur near 0400 L.M.T. The winds thus blow from the daylit hemisphere to the nightside of the earth across the polar regions and the sunrise-sunset lines.

The driving force $-\frac{\nabla p}{\rho}$ has to be calculated from atmospheric data, and several authors have used data given by Jacchia (1965) for medium sunspot cycle and equinoctial conditions. The winds are influenced by

1. Coriolis force $= 2\rho(\underline{u} \times \underline{\omega})$

2. Viscous force $= \rho\mu\left(\frac{\partial^2 \underline{u}}{\partial h^2}\right)$

3. Inertial force $= \rho\left[\frac{\partial^2 \underline{u}}{\partial t} + (\underline{u} \cdot \nabla)\underline{u}\right]$

4. Ion drag experienced by neutral particles given by

$$\rho\nu_n(\underline{u} - \underline{u_i}) = \frac{\rho\nu_i N_i}{N_n}(\underline{u} - \underline{u_i})$$

In the above expressions

p - atmospheric pressure

ρ - atmospheric density

$\underline{\omega}$ - frequency of earth's rotation

$\underline{u}$ - atmospheric wind velocity

μ - kinematic coefficient of viscosity

ν_n - collision frequency of neutral particle with all ions

ν_i - collision frequency of ion with all neutrals

$\underline{u_i}$ - ion velocity

N_i - ion concentration

N_n - neutral particle concentration

Assuming that electric fields are not involved, and that ions move mainly in the direction of the earth's magnetic field, Kohl and King (1967) obtain the equation of motion for the atmosphere as

$$\frac{\partial \underline{u}}{\partial t} - \mu\frac{\partial^2 \underline{u}}{\partial h^2} - 2(\underline{u} \times \underline{\omega}) + \frac{\nu_i N_i}{N_n}\left[\underline{u} - (\underline{u} \cdot \underline{t})\underline{t}\right] = -\frac{1}{\rho}\nabla p$$

where $\underline{t}$ is the unit vector in the magnetic field direction.

As a lower boundary condition, it is assumed that at around 120 km the air is stationary, and all parameters are constant. This assumption isolates the thermospheric motions from any motions at lower heights, and though inaccurate for levels in the vicinity of 120 km it is all right for larger heights. The equation of motion is then solved to obtain the value of $\underline{u}$.

For a height of 300 km Kohl and King (1967) obtain a wind velocity of 40 m/sec for an electron density of $10^6/cm^3$, and 150 m/sec for an electron density of $(3 \times 10^5)/cm^3$. Geisler (1966, 1967 b) obtains typical speeds of order 100m/sec. This implies that such an air-cell can travel some thousands of kilometers within the course of a day.

The diurnal variation of these wind-vectors at 300 km for different latitudes is shown in Fig. 2.2. (Pg. 29(a)) after Geisler (1967 b).

2.5 F_2-region anomalies

The F_2-region anomalies are a consequence of the transport effects which determine its behaviour apart from simple production and loss. The F_2 region does not obey the simple Chapman law; at equatorial and polar latitudes, very

often night-time F_2 frequencies are higher than daytime ones. The ionospheric F-region shows Annual, semi-annual, geomagnetic and seasonal anomalies which have been studied by many workers (Berkner et al., 1936; Appleton 1935; Rishbeth and Setty 1961; Taylor 1966; Bannon and Wood 1964; Yonezawa 1959; Yonezawa and Arima 1959).

(a) The annual variation - refers to world-wide N_mF_2 being higher in December than in June by about 20%. About 6% of this can be accounted for by the reduced sun-earth distance in December, and the consequent increase in ionising solar flux. The remaining 14% increase is still to be accounted for. The annual variation is seen under conditions of both high and low sunspot.

(b) The semi-annual variation of N_mF_2 shows increased values twice a year during the equinoxes (Yonezawa, 1959) in magnitude often as large as the December values. These maxima coincide with the semi-annual variation in neutral air temperature (Jacchia 1963), and are possibly related to them. Semi-annual variations have been observed in $h_{max}F_2$ (Becker, 1966). The semi-annual variation in N_mF_2 shows up most at the low latitudes and in the southern hemisphere, as it is masked by the winter anomaly at higher latitudes. It is observed during low sunspot conditions (Yeh and Flaherty 1966; Yuen and Roelofs, 1967).

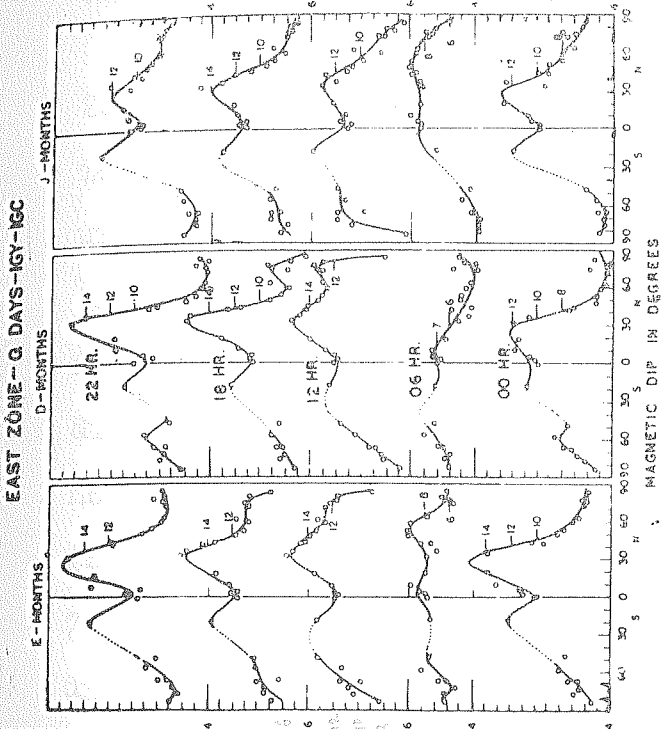
(c) The geomagnetic anomaly

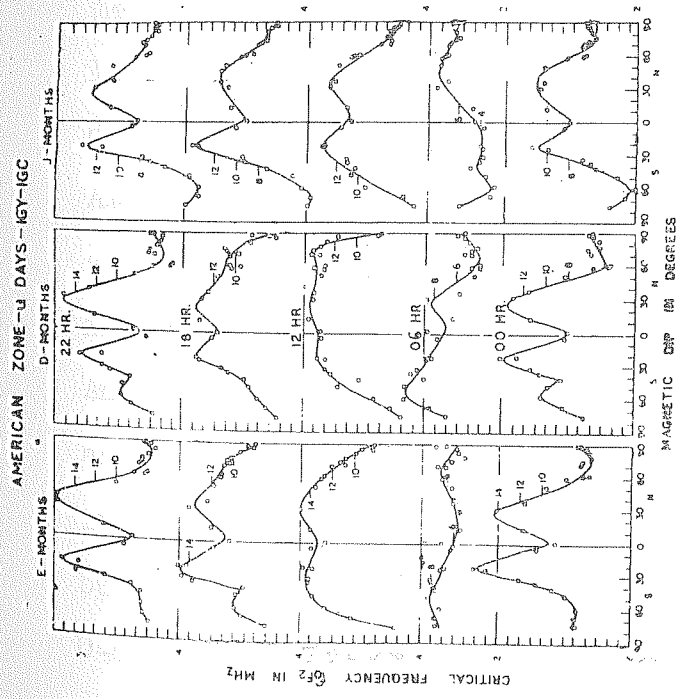
This refers to the observation that noontime f_oF_2 does not achieve largest values at the equator but is found at regions of 20°N and 20°S geomagnetic latitude even in the equinoxes (Appleton 1946). As early as 1942 K.Maeda et al ., showed that f_oF_2 variation at American and Asian stations tallied better if geomagnitude latitude was used rather than geographic. Rastogi (1959 a, b) showed that the latitudinal distribution of noon f_oF_2 showed far less scatter if dip were used rather than dipole latitude. The symmetry is thus found to be about the dip equator rather than about the geographic or geomagnetic equator. The equatorial regions lie in the anomaly trough while the regions of maximum electron density are referred to as the anomaly peaks or crests. These anomaly crests vary in magnitude and position with time of the day, season, solar cycle epoch, longitude etc., and have been the subject of work by many authors[Rastogi (1966); Rao and Malhothra (1964); L.Thomas (1968); Lyon and Thomas (1963); C.M. Rush et al., (1969).]

The diurnal development of the F_2 anomaly for the equinoctial months of low sunspot years (1953-54) was studied in detail by Rastogi(1959). The same for the high sunspot years (IGY-IGC) has been done by Sanatani in his Ph.D thesis (1966).

The main features of the development of the F_2 anomaly are summarised in Fig. 2.3 (Pg. 41 (a)). The first two blocks compare the development of the anomaly in the American zone and the East zone during the IGY-IGC years (high sunspot years). The development is shown every six hours for magnetically quiet days, for the three seasons separately. The apparent features are:

1. The anomaly is flattest at 06 hr. and most pronounced at 22 hr. and 00 hr. This itself is unusual, as the cause of the anomaly is believed to be the upward $\vec{E} \times \vec{B}$ lifting force over the equator and would be expected to be strongest around midday. When one compares the curve for 12 hr. and 22 hr. it is clear that the anomaly peak frequencies remain unchanged at night, while the trough frequencies have dropped by almost 5 Mc. This is understable if one assumes a downward $\vec{E} \times \vec{B}$ drift at the equator at night, driving charged particles into the regions of greater loss. A time-lag of 10 hr. between the maximum upward $\vec{E} \times \vec{B}$ lifting force, and the maximum anomaly development is hardly accountable. This feature is most pronounced in both zones in the E-months when the maximum post-sunset rise (see Section 2.7) in equatorial $h_{max} F_2$ occurs. In the D-months it is greater in the American zone than in the East zone. It is less in both zones in the J-Months, when the post-sunset rise in $h_{max} F_2$ at equatorial stations is less. It is quite likely that the enhanced night-time F_2 anomaly in high sunspot years is connected with this equatorial post-sunset


EAST ZONE-Q DAYS-IGY-IGC
E-MONTHS
D-MONTHS
J-MONTHS
22 HR.
18 HR.
12 HR.
06 HR.
00 HR.
CRITICAL FREQUENCY foF2 IN MHz
MAGNETIC DIP IN DEGREES


AMERICAN ZONE-U DAYS-IGY-IGC
E-MONTHS
D-MONTHS
J-MONTHS
22 HR.
18 HR.
12 HR.
06 HR.
00 HR.
CRITICAL FREQUENCY foF2 IN MHz
MAGNETIC DIP IN DEGREES

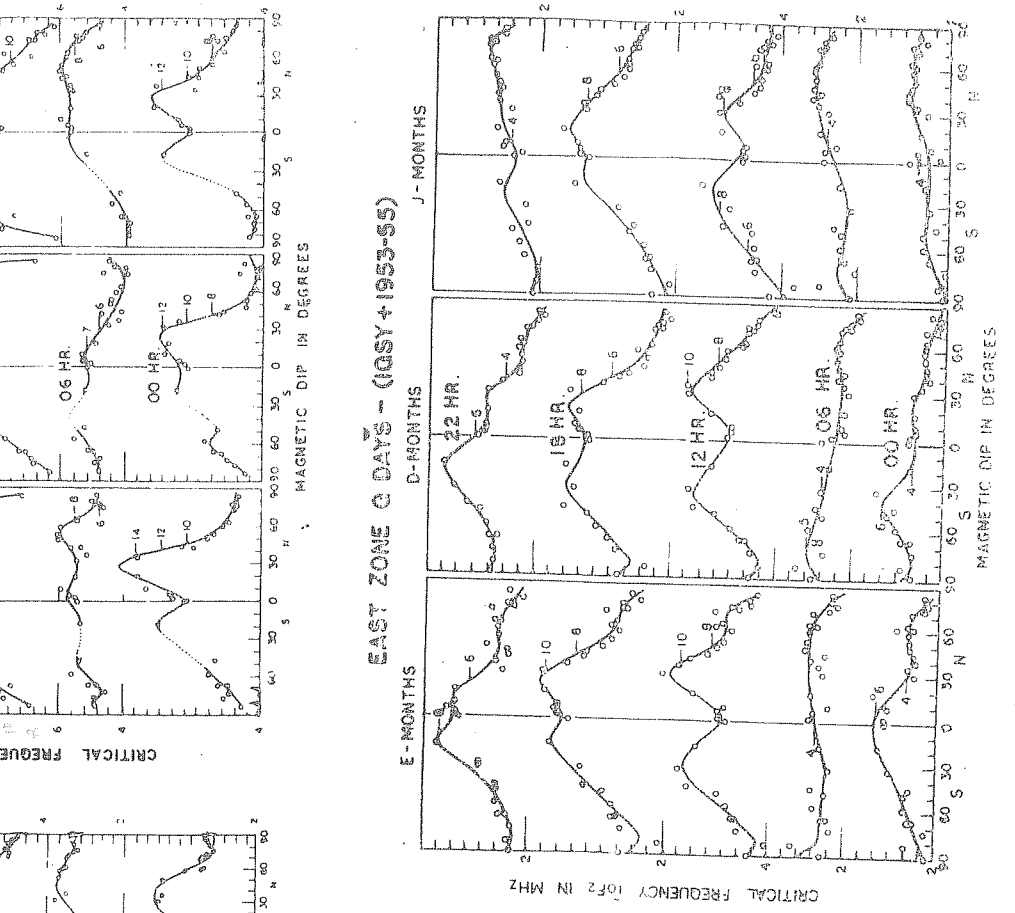

EAST ZONE Q DAYS - (IQSY+1953-55)
E-MONTHS
D-MONTHS
J-MONTHS
22 HR.
18 HR.
12 HR.
06 HR.
00 HR.
CRITICAL FREQUENCY foF2 IN MHz
MAGNETIC DIP IN DEGREES

Fig. 2.3

height rise of ionisation.

2. The winter spur relates to the observation that there is a sudden rise in f_oF_2 at a magnetic dip of 70° in the winter hemisphere in the daytime. Much work has been done on this by Croom et al., (1960), J.O. Thomas (1962, 1963), and it is believed that such a spur exists only in the daytime and disappears at night. The D-month curves in Fig. 2.3 (Pg.41 (a)) however show that in both zones there is a spur at 60°S (Summer hemisphere) at 22 hr. and 00 hr. The spur seen at 70°N dip in the daytime seems to have shifted over to 60°S dip at night. It is possible that this feature has shown up prominently bedause purely quiet days were used instead of median values;as will be shown later (Chapter 5) the spur is levelled out on Disturbed days. It may be noticed that the daytime spur is more prominent in the East Zone than in the American zone where it saturates out. In the J-months, the spur shows up in the daytime at 70°S dip (winter hemisphere) in the East zone, but is not visible at all in the American zone. This brings out a marked longitudinal asymmetry in its occurrence. There is a slight suggestion of its being at 70°N dip at 22 hr. and 00 hr. in the East zone, but the shift is certainly not as prominent as in the D-months. In the East zone, in the E-months too, the spur occurs at 12 hr and 18 hr. at 70°N dip. If this night-time reversal of the spur is connected with the night-time

reversal of the F_2 seasonal anomaly, it is likely that the causes of the two are the same. This point could do well with some investigation.

Other salient differences between the two longitude zones are that in general, certainly so in the E and D months, the northern anomaly peak is higher in the East zone, while the American zone does not exhibit a difference too clearly. The diagrams on the right-hand side of Fig. 2.3 (Pg. 41 (a)) compare the development of the anomaly in the East zone between IGY-IGC (high sunspot years) and IQSY + 1953-55 (low sunspot years) in a similar way. The prominent differences are -

1) Overall frequencies are much lower in low sunspot years as is to be expected.

2) In the low sunspot years the anomaly trough is deepest at 12 hr. and flattens out in the night-time hours - this behaviour is opposite to the high sunspot years. In both epochs however, the anomaly is flattest at 06 hr.

3) A slight tendency for a spur continues to be seen in the low sunspot years in the E-months around 70°N dip. It is not seen in the other seasons (Thomas, 1964).

4) In the low sunspot years equatorial trough frequencies do not change as drastically from day to night, as they do in high sunspot years.

(d) The seasonal anomaly - refers to mid and high-latitude daytime F_2 critical frequencies being larger in winter than in summer; the feature vanishes at night. In the northern hemisphere, the winter anomaly and December anomaly add up to give greatly enhanced values of N_mF_2. Unlike the annual and semi-annual anomalies in N_mF_2, the winter anomaly occurs only in the high sunspot years. The winter spur at 70° dip is a special feature of the seasonal anomaly showing that it is most enhanced at a locus of dip angle $I = 70^o$. In the southern hemisphere, N_mF_2 seems to depend more on geographic latitude (Sato and Rourke 1964). Rishbeth and Setty (1961) found that just after layer sunrise, dN/dt in the F_2 layer is larger in winter than in summer. Increase in electron density seems to start at solar zenith angle $\chi = 97^o$ in winter, and at a smaller zenith angle $\chi = 93^o$ in summer.

Most of the features of the seasonal anomaly described above can be seen in Fig. 2.4 (Pg. 45 (a)). Here the variation of December and June solstitial f_oF_2 with magnetic dip for the midday hours (averaged 10 hr. to 14 hr.) and the midnight hours (averaged 22hr. to 02 hr.) are shown for magnetically quiet days. The longitudinal differences are brought out by comparing the West zone and the East zone for IGY-IGC. The salient differences are:

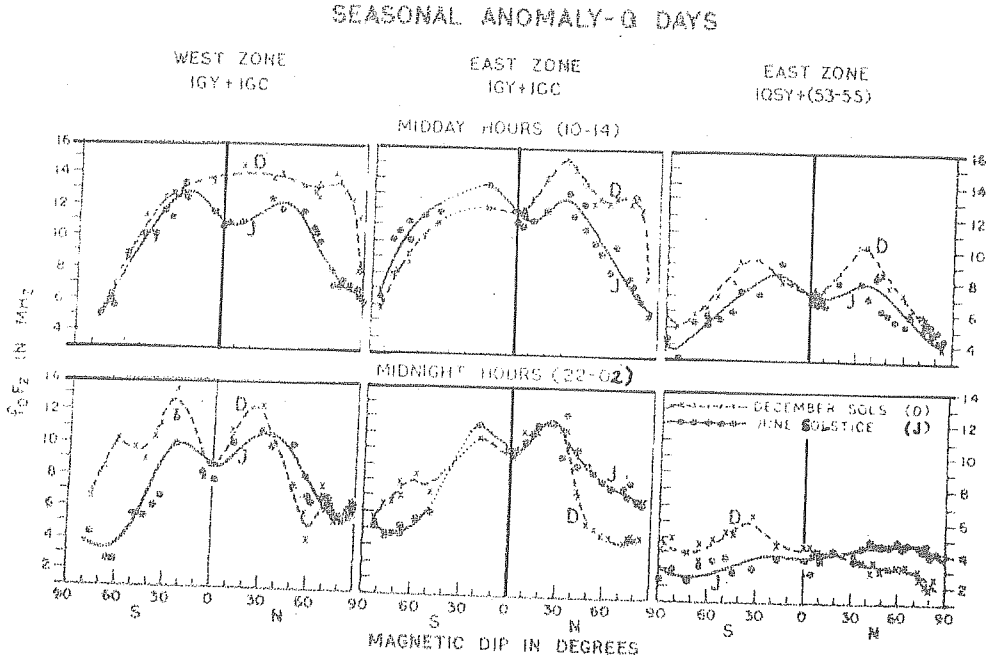
1) At midday, the equatorial anomaly is completely masked in the West zone in the D-months although it is

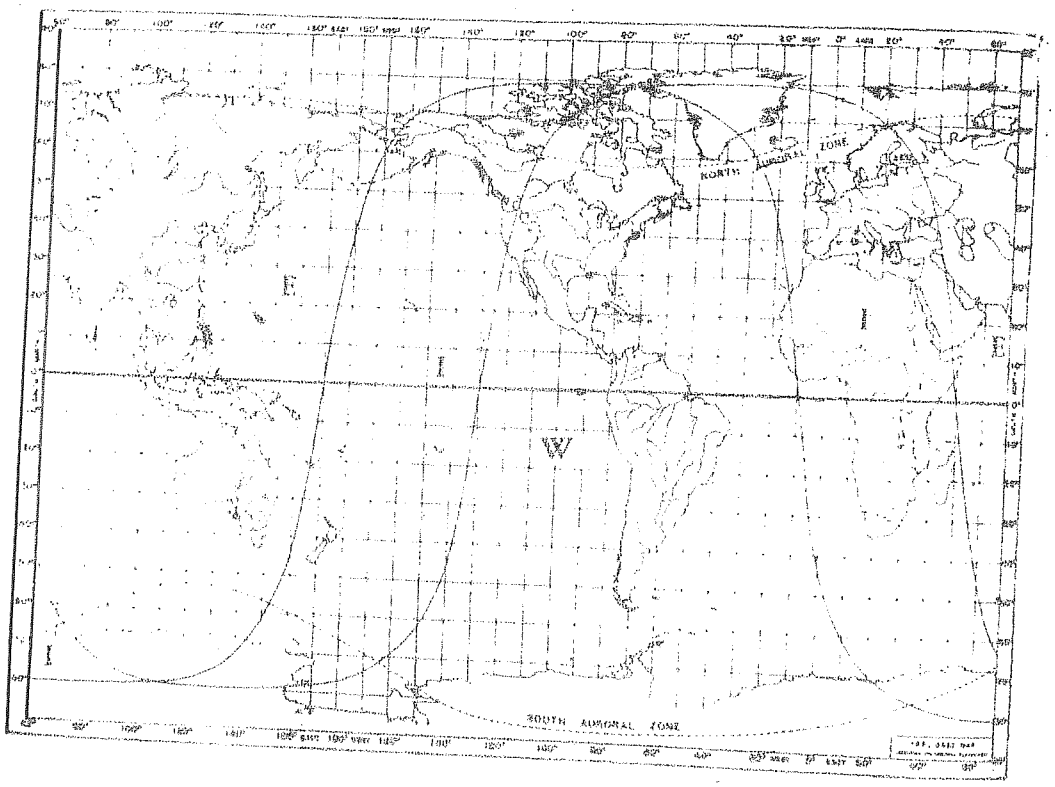
clear in the East zone. The winter spur at 70°N dip shows up better too in the East zone than in the West zone. In most of the southern hemisphere there is little difference between the D-month and J-month f_oF_2 in the West zone, but in the East zone, June solstice values (winter hemisphere), are distinctly greater than December solstice values. While the cross-over of the two curves occurs at the dip equator in the East zone, there is a vast difference at the dip equator in the West zone.

2) In both East and West zones it is interesting to see that the December spur at 70°N dip in the daytime has shifted over to 60°S dip at night-time; this has been pointed out earlier. This feature is a notable one, and is worth further investigation. It could have something to do with the sunward tilt of the geomagnetic axis with respect to the geographic axis, or the direction-reversal of neutral winds at night.

3) The night-time D-month f_oF_2 values seem to be more pronounced in the southern hemisphere of the West zone than of the East zone as compared to the J-month f_oF_2 values. This is so too in the low latitudes of the northern hemisphere in the West zone. In the East zone, there is little difference between D-month and J-month values, at low latitudes, but there is large difference beyond 30°N dip.

FIG - 2.4





World map showing East (E), West (W), and Intermediate (I) zones(CRPL Base Map)

FIG - 2.5

The solar cycle features of the seasonal anomaly are brought out by comparing the East zone during theIGY-IGC, and (IQSY + 1953-55) in Fig. 2.4 (Pg. 45 (a))

The prominent features are:-

1) During low sunspot years too, D-month values are greater than J-month values in the daytime, the maximum difference being at 40° dip latitude . The winter spur is not seen in either hemisphere, by day or by night.

2) At night, the December anomaly is seen in low sunspot years only in the southern hemisphere; in the northern hemisphere, there is a reversal, with June solstice values being larger. The cross-over of the two curves is at the dip equator by day, and slightly north of it at night.

2.6 World-wide variations of quiet-day f_0F_2

The existence of a longitudinal effect in quiet-time F_2 behaviour was recognised early by several workers (Ranzi 1939; Bailey 1948; Liang 1947; Appleton 1950) The classification of the world map into the longitude zones East (E), West (W), and Intermediate (I) was done [Minnis (1952) and Appleton (1947)] such that in each zone the change of geomagnetic latitude for a given geographic latitude is not too great. Also in the West zone, the magnetic equator is farthest south of the geographic equator while in the East

zone it is farthest north. In the Intermediate zone the two cross each other. Studies revealed that the variations of f_oF_2 also depend on the magnetic declination of the place of observation (Eyfrig 1963).

Such a world map showing the E,W, and I zones is shown in Fig. 2.5 (Pg. 45(a)). It is worth mentioning that the two zones chosen for our study correspond well with the W and the E zones. The variations of f_oF_2 at the longitude zones E and W for different seasons and different sunspot cycles are shown in Fig. 2.6 (Pg. 47(a)). They are shown in the form of contours of quiet-time f_oF_2 against latitude and time.

During the high sunspot years of IGY-IGC the general appearance of the contours in both East and West zones is fairly similar; most differences occur in the regions of the anomaly crests. In the E-months, the contours are truly symmetrical about the dip equator in both zones, with highest frequencies occurring around midday in the regions of the Appleton anomaly crests ($\pm 30^{\circ}$ dip). In the D-months, the crowding of contour lines in the winter hemisphere is seen with a large density of lines in the daytime hours around 75°N dip, and around 40°N dip after 18 hr. A fewer number of contour lines are seen in the summer hemisphere. In the J-months the crowding of lines is more in the southern (winter) hemisphere; minor

47(a)

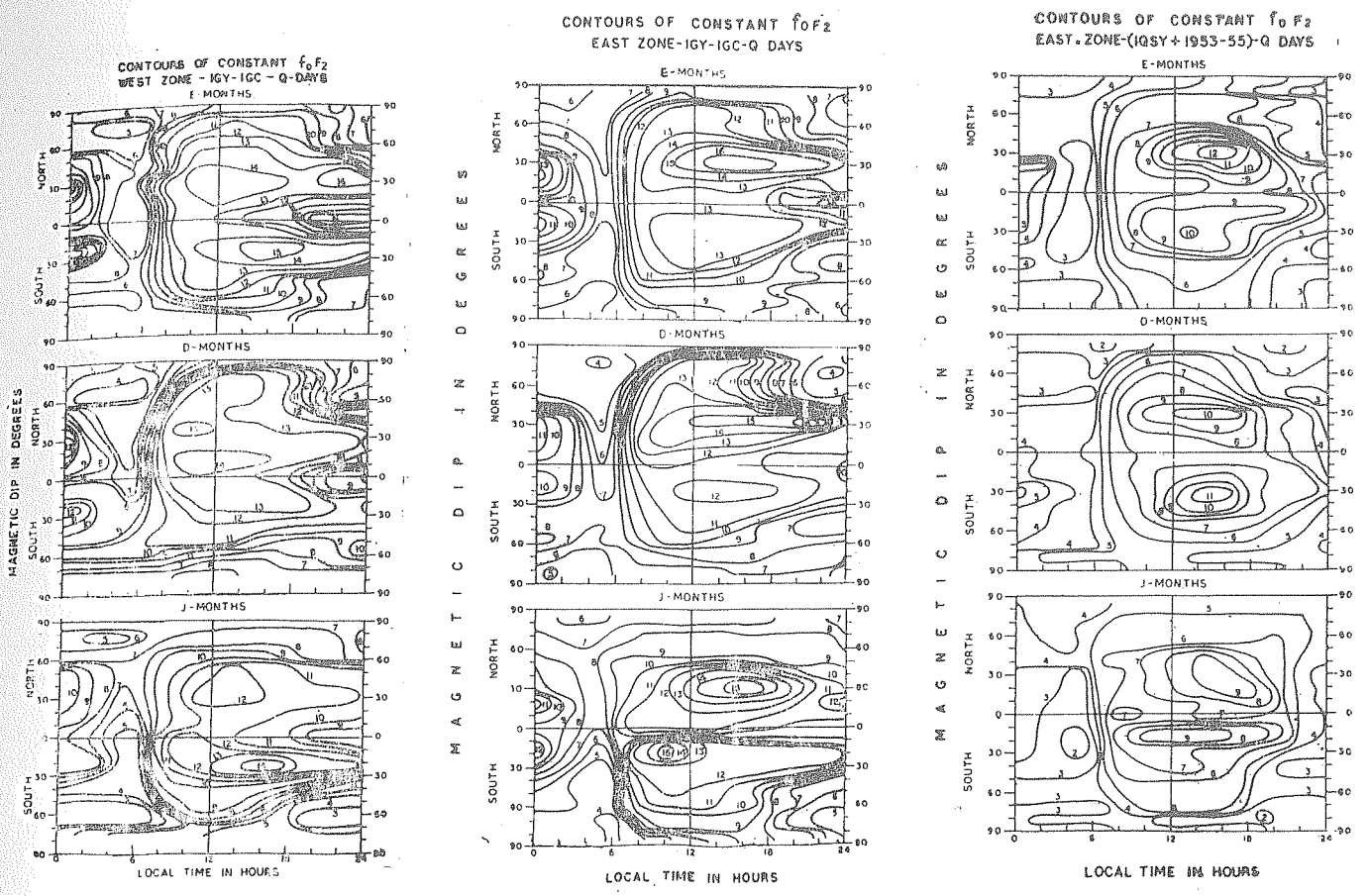


Fig. 2.6

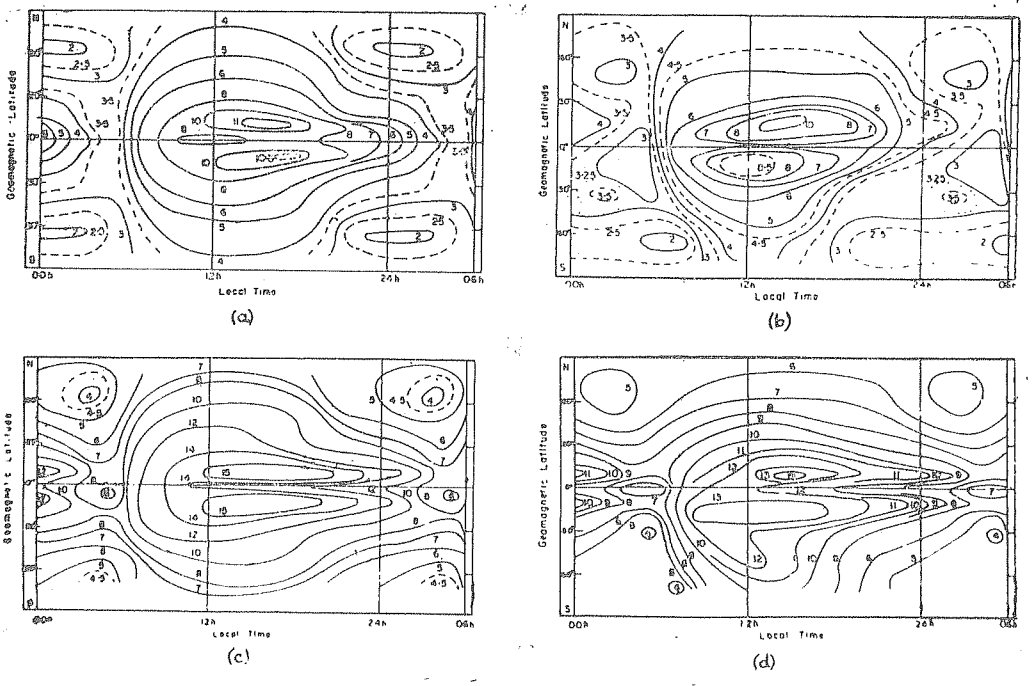


Fig. 2.7 : Maps of f_0F_2 median values (Martyn 1959) 1943–1944, low sunspot (a) equinox (b) June solstice; 1947, high sunspot (c) equinox (d) June solstice.

differences like maximum frequencies being attained in the forenoon hours in the East zone, and in the afternoon hours in the West zone can be observed.

In the D-months this is reversed, with the East zone experiencing highest frequencies after noon, and the West zone doing so at forenoon.

Notable differences between the high sunspot years (IGY-IGC) and the low sunspot years (IQSY) for the East zone are clearly seen. During IQSY, the marked crowding of contour lines seen in the winter hemisphere of IGY-IGC is not seen. In the E-months, the contour lines are perfectly symmetrical about the dip equator; in the D and J-months too, there is a fair amount of symmetry with a slightly closer spacing of lines in the winter hemisphere.

The various anomalies of the F-region described in the previous sections can be seen from these contour diagrams. It is interesting to compare these contour diagrams with Martyn's (1959) contour diagrams of f_oF_2 for the epochs 1943-1944 (sunspot minimum) and 1947 (sunspot maximum) shown in Fig. 2.7 (Pg. 47 (a)).

ELECTRON DENSITY DISTRIBUTIONS AT TRUE HEIGHTS ON QUIET DAYS

2.7 Solar cycle and seasonal studies at equatorial station Kodaikanal.

Electron density distributions on magnetically quiet days at Kodaikanal (+ 3.6° dip) have been obtained by reducing ionograms to true height profiles by the Budden's Matrix method (Budden 1954). The diurnal, seasonal, and solar cycle variations of electron density have been studied.

(a) Daily variation of $h_{max}F_2$, y_m, N_T, $N_{max}F_2$

Fig. 2.8 (Pg. 50 (a)) shows the daily variations of the following parameters:-

(1) $h_{max}F_2$ - the true maximum height of the F_2-layer

(2) y_m - the semi-thickness of the F-layer (this is also twice the scale height and is therefore proportional to temperature.)

(3) N_T - the total electron content from h_mF_2 to the ionospheric base

(4) $N_{max}F_2$ - the maximum electron density at the F_2 peak.

The variations are shown for 3 typical seasons - January (winter), April (equinox) and July (summer) for 3 solar cycle epochs - 1958 (high sunspot), 1961 (medium sunspot), and 1964 (low sunspot).

The main feature can be summarised thus:-

(1) In general, $h_{max}\ F_2$ reaches its minimum value at 06 hr. and its maximum value a little later than 18 hr. The clarity of these features decreases with decreasing sunspot as also the absolute height of F_2. In the July months, the post-sunset rise is not clear even in 1961. In 1964, $h_{max}\ F_2$ follows a flat variation in all seasons. The post-sunset rise in $h_{max}\ F_2$ is not clearly understood; it has been attributed to $\vec{E} \times \vec{B}$ drift (Martyn 1959), Calvert (1962) believed the $\vec{E} \times \vec{B}$ force to arise from electric fields induced by the downward motion of the suddenly cooled-neutral atmosphere across the geomagnetic field lines.

2) The semi-thickness y_m becomes maximum after mid-day, and the minimum values are attained at 06 hr, and 18 hr. This is true for all sunspot years . It is important that in July there is hardly any difference between the different years. In the other months semi-thickness decreases with decreasing sunspot, the change being markedly larger in the hours after the peak in $y_m F_2$ is reached. There is no post-sunset rise in semi-thickness y_m. This strong diurnal variation in slab thickness of the layer at the magnetic equator was observed by Ross and Blumle (1962) and interpreted as the $\vec{E} \times \vec{B}$ vertical uplift.

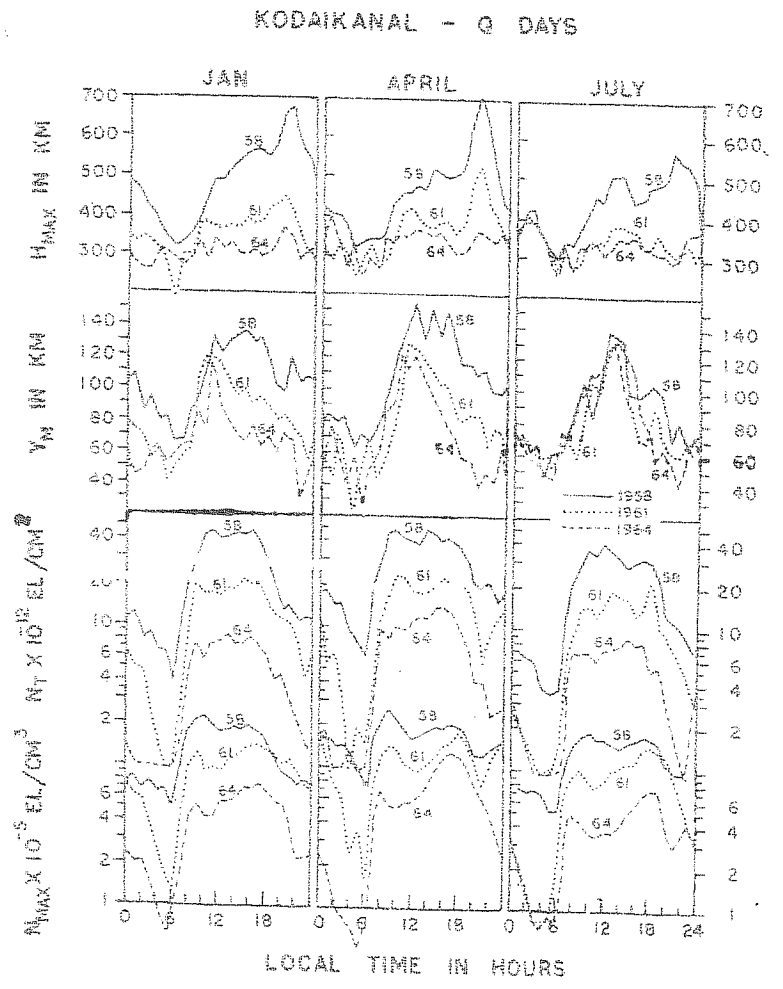

KODAIKANAL - Q DAYS
JAN
APRIL
JULY
h_{MAX} IN KM
y_M IN KM
$N_{MAX} \times 10^{-5}$ EL./CM^3 $N_T \times 10^{12}$ EL/CM^2
1958
1961
1964
LOCAL TIME IN HOURS

FIG. 2·8

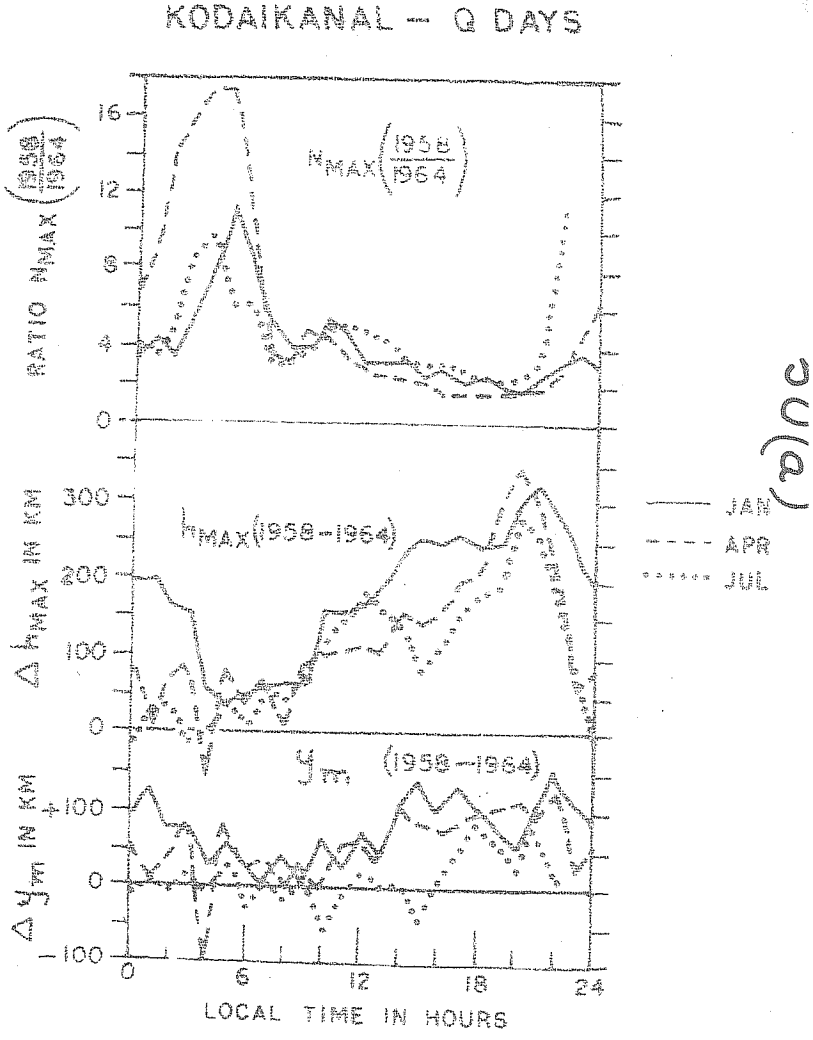

KODAIKANAL -- Q DAYS
RATIO $h_{MAX}\left(\frac{1958}{1964}\right)$
Δh_{MAX} IN KM
$h_{MAX}(1958-1964)$
Δy_M IN KM
y_M (1958-1964)
JAN
APR
JUL
LOCAL TIME IN HOURS

FIG. 2·9

3) At 06 hr. both $h_{max}\ F_2$ and y_m reach their minimum values which shows the ionosphere is thinnest at that time. At midday, both $h_{max}\ F_2$ and y_m increase when the ionosphere is thickest. At sunset time, $h_{max}\ F_2$ increases but y_m does not, which shows that at this time, the ionosphere moves up as a whole.

4) The variations of N_T and N_{max} are similar. Minimum values are attained at 06 hr. and maximum values in the daytime. The magnitudes decrease with decreasing sunspot. The midday bite-out is better seen in $N_{max}\ F_2$ than in N_T In $N_{max}\ F_2$, the fore-noon peak is prominent in 1958, while the post-noon peaks are larger in 1961 and 1964. This feature at Kodaikanal has been studied by Bhargava and Subrahmanyan (1962)

(b) Changes in $h_{max}\ F_2$, y_m, and $N_{max}\ F_2$ from low to high sunspot.

The solar cycle changes in the parameters $h_{max}\ F_2$, y_m, and $N_{max}\ F_2$ from low to high sunspot are shown at Kodaikanal by taking the ratio of N_{max} (1958) to N_{max}(1964) and the difference between 1958 and 1964 of $h_{max}\ F_2$ and y_m. These are shown for the different hours in Fig. 2.9(Pg.50(a)); the full lines show the changes in January, the dashed lines in April, and the dotted lines in July. The largest changes in N_{max} occur between 00 and 06 hr, and are most pronounced in April; there is some change after 20 hr too.

$h_{max}\ F_2$ does not show much change in the morning hours when $N_{max}\ F_2$ changes, but it starts gradually before noon, reaching peak difference at 18 hr. which is the time when the post-sunset rise in height commences in high sunspot years. There is no pronounced difference between the different months. y_m too shows larger changes in the hours after noon in sympathy with the $h_{max}\ F_2$ variations, but the curves are flatter especially that for July.

(c) Contours of constant electron density.

Contours of constant electron density are depicted in Fig. 2.10 (Pg. 52 (a)) for all heights ranging from 100 km to 700 km. The dotted lines depict the $h_{max}\ F_2$ level, and the density distributions at higher levels are obtained by fitting the topside to the F_2 peak, assuming a Chapman distribution. The values on the contour lines represent the electron density in 10^5 electrons/cm^3. From this diagram, the seasonal variations as well as the solar cycle variations can be clearly seen. The main features which emerge are:

1) There is a general steep crowding of lines in all months around sunrise and sunset corresponding to the sudden changes in electron density distributions at these times. Such crowding is more below the $h_{max}F_2$ level than above.

52(a)

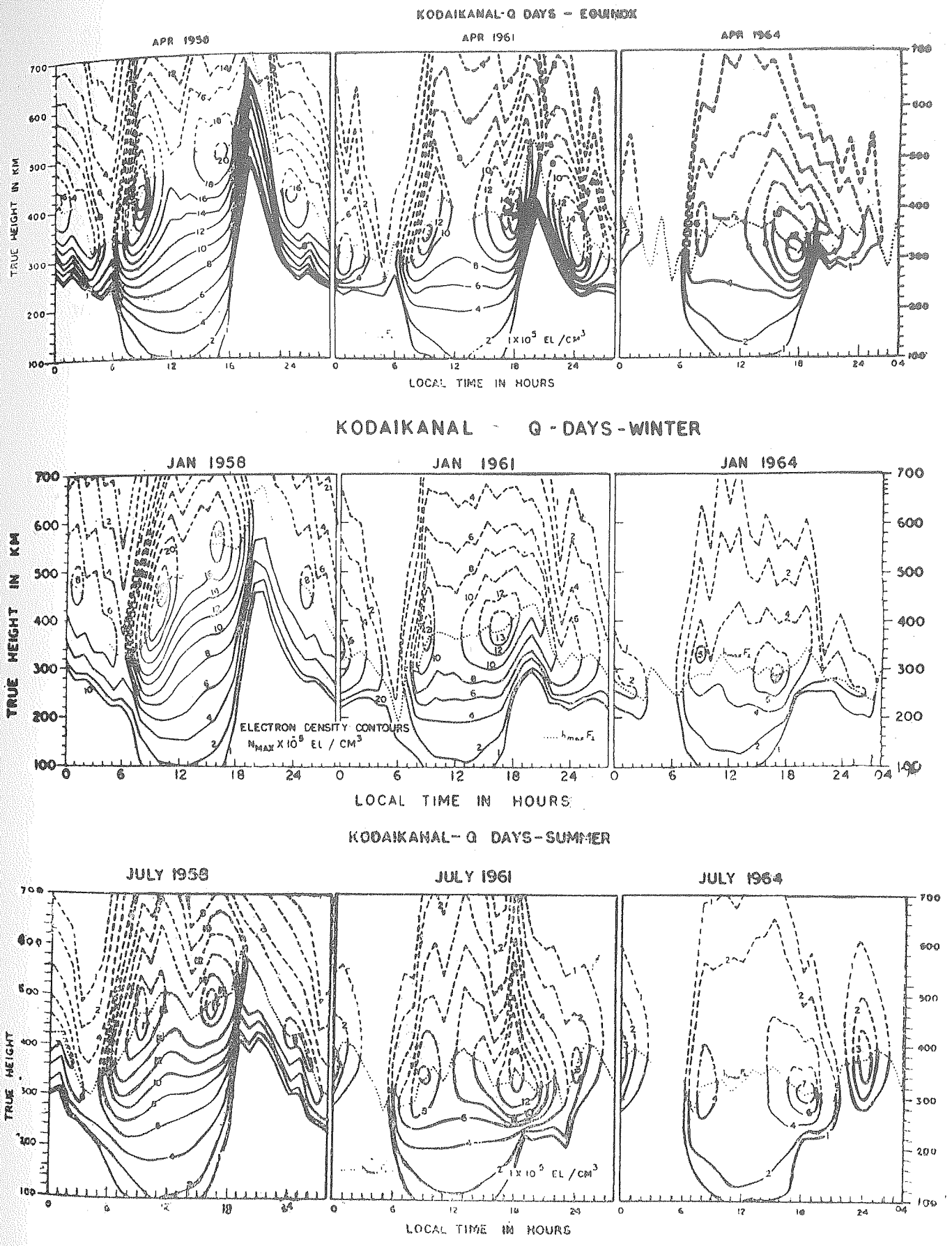

KODAIKANAL-Q DAYS – EQUINOX
APR 1958
APR 1961
APR 1964
TRUE HEIGHT IN KM
1 X 10⁵ EL/CM³
LOCAL TIME IN HOURS
KODAIKANAL – Q-DAYS-WINTER
JAN 1958
JAN 1961
JAN 1964
TRUE HEIGHT IN KM
ELECTRON DENSITY CONTOURS
N_MAX X 10⁵ EL / CM³
h max F₂
LOCAL TIME IN HOURS
KODAIKANAL – Q DAYS-SUMMER
JULY 1958
JULY 1961
JULY 1964
TRUE HEIGHT
1 X 10⁵ EL/CM³
LOCAL TIME IN HOURS

Fig. 2.10

2) Largest electron densities occur in April (equinoxes) less in January (winter) and least in July (Summer). In any season, electron density decreases with decreasing sunspot. The maxima in electron density seen before noon and afternoon correspond to the peaks bordering the mid-day bite-out. These change with sunspot in the following way -

Month	Forenoon peak in el/cm.^{3}		
	1958	1961	1964
January	24×10^5	12×10^5	5×10^5
April	26×10^5	14×10^5	6×10^5
July	17×10^5	10×10^5	4×10^5

Month	Afternoon peak in el./cm.^{3}		
	1958	1961	1964
January	18×10^5	13×10^5	7×10^5
April	20×10^5	18×10^5	12×10^5
July	17×10^5	14×10^5	7×10^5

3) Post-sunset rise in height is most pronounced in 1958, less in 1961, and negligible in 1964. It is strongest in April, less in January, and least in July.

4) Ionisation almost vanishes just before sunrise (06 hr) in all seasons of 1964; 1961 shows an intermediate behaviour with evidence of this feature only in July. In 1958, however, a good amount of ionisation persists right till larger heights before sunrise.

5) Ionisation at the lowest heights of 100-150 km is least affected by season or solar cycle. This supports the observations of Wright (1962) whose analysis of noon density profiles for Huancayo (dip $2^{o}N$) showed that the effect of solar activity is more on the F_2 region, with little or no change at the E and F_1 regions.

6) The ionisation density at higher heights in the night-time hours progressively decreases through 1958, 1961 and 1964.

(d) Electron density variations at constant heights

Fig. 2.11 (Pg. 54 (a)) shows the electron density variations at constant heights for Kodaikanal for the same months - for January (winter), April (equinox), and July (summer) of 1958, 1961 and 1964. The heights are indicated against the variation lines, and the electron density values

54(a)

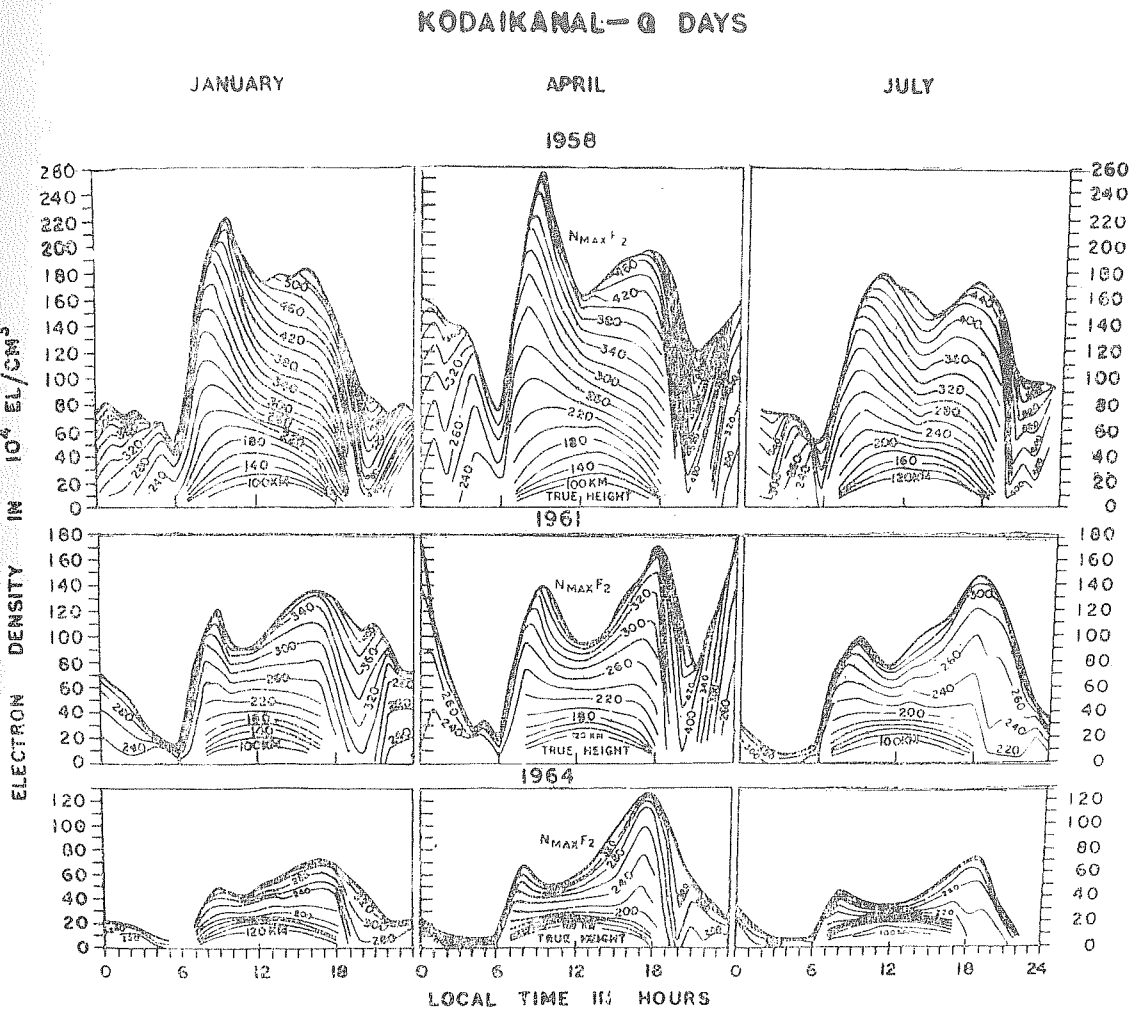

KODAIKANAL— Q DAYS
JANUARY
APRIL
JULY
1958
1961
1964
ELECTRON DENSITY IN 10^4 EL/CM^3
$N_{MAX}F_2$
100KM
TRUE HEIGHT
LOCAL TIME IN HOURS

Fig. 2.11

are in 10^4 el/cm^3. The thick line bounding each set of curves is the N_{max} F_2 level. The midday bite-out feature is seen in all the figures and starts only at heights above 200 km. It may be noted that it is the forenoon peak which is pronounced in 1958, while the afternoon peak becomes pronounced in 1961 and 1964. The sharp gradient in electron density at sunrise and sunset is clearly seen. In each year, equinoctial electron densities are largest. With decrease in sunspot, there is a progressive decrease in electron density, and in July 1964 the variation is almost flat. The diagrams suggest that the forenoon and afternoon peaks at all heights lie on a smooth curve which completes somewhere above the N_{max} F_2 level.

2.8 Longitudinal differences in electron density distributions at equatorial stations

These studies compare electron density distributions during identical periods at the equatorial stations Huancayo (75°W) and Kodaikanal (75°E). It may be recapitulated that the former is located in a region of low geomagnetic field, and the latter in a region of large geomagnetic field. Comparisons were made for the International Quiet Days of 3 seasons - January, April and July - for the years 1961 (medium sunspot) and 1964 (low -sunspot).

(a) Comparison of $h_{max}\ F_2$, y_m, N_T and $N_{MAX}\ F_2$

Comparisons of $h_{max}\ F_2$, y_m, N_T and $N_{max}\ F_2$ are shown in Fig. 2.12 (Pg. 56(a)) Some striking points are:

1) Longitudinal differences show out more in 1961 than in 1964. In April and July of 1964, there is very little difference, though in January some difference is seen.

2) In January and July of both years, $h_{max}\ F_2$ at Huancayo is more than at Kodaikanal. April variations are uncertain; it appears as though in 1961, Kodaikanal heights are more, but nothing can be said of 1964. The post-sunset height rise is shown at both stations in January and April of both years. In July it is not too clear. The height variations in 1964 are flatter.

3) y_m reaches a maximum just before midday, in all seasons in both years. Semi-thickness in April and July is larger than in January, notably in 1964. Minimum y_m occurs around 06 hr. In 1961, in January and April, y_m at Kodaikanal is larger than at Huancayo; in July this trend is seen prominently around midday and less at other hours.

4) In general N_T attain higher values at Kodaikanal than Huancayo in April and July of both years though the July 1964 behaviour is uncertain. In January of both years,

56(a)

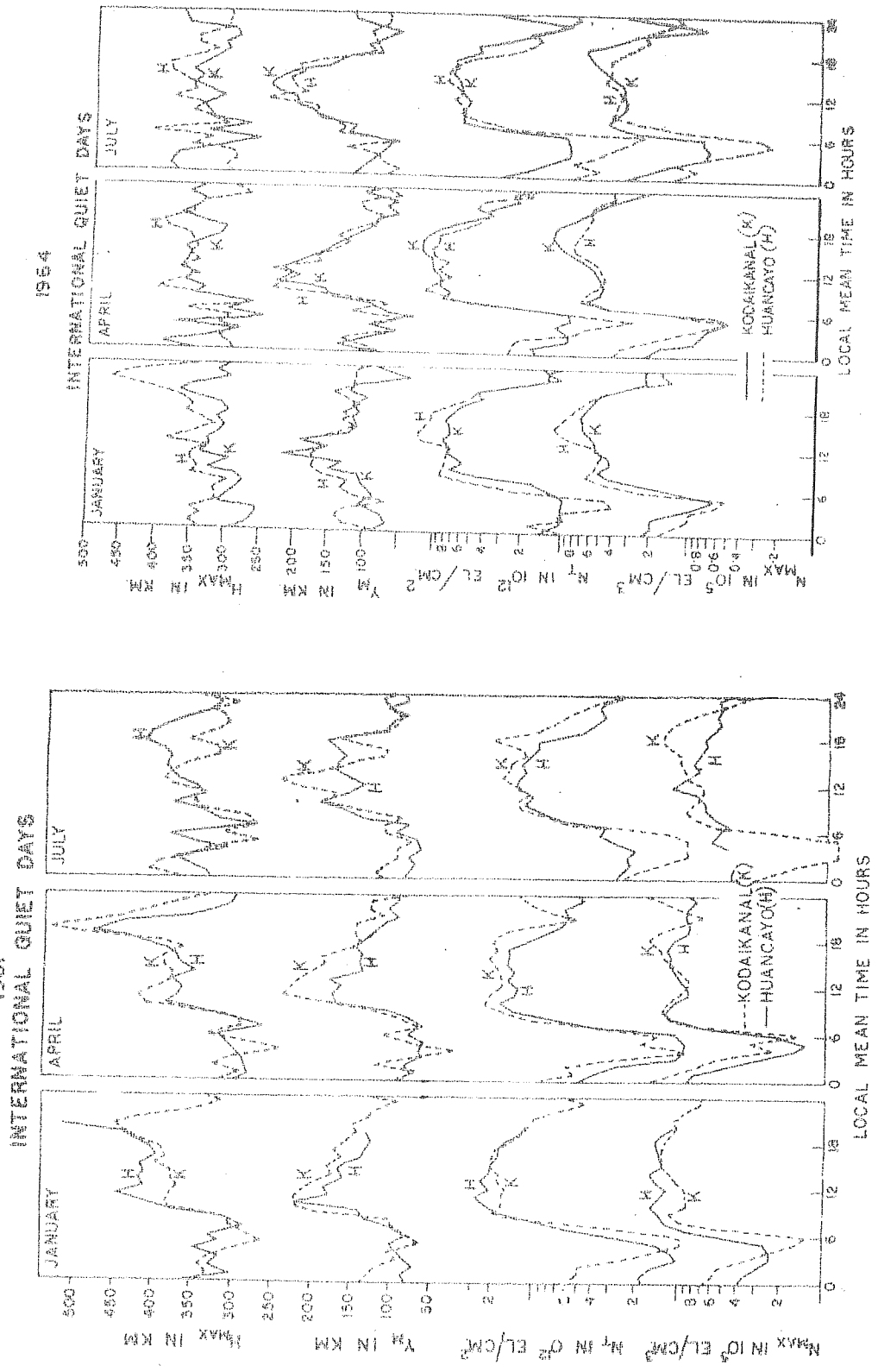

1954
INTERNATIONAL QUIET DAYS
JANUARY
APRIL
JULY
KODAIKANAL (K)
HUANCAYO (H)
LOCAL MEAN TIME IN HOURS
1951
INTERNATIONAL QUIET DAYS
JANUARY
APRIL
JULY
KODAIKANAL (K)
HUANCAYO (H)
LOCAL MEAN TIME IN HOURS

FIG 2.12

this is reversed, the total electron content over Huancayo being larger than over Kodaikanal. In both zones, N_T is decreased in 1964 as compared to 1961 in all seasons; maximum values occur in the day-time hours.

5) $N_{max}\ F_2$ variations follow N_T variations as regards comparison between Huancayo and Kodaikanal. The midday bite-out phenomenon is seen more clearly in $N_{max}\ F_2$ and in both zones is pronounced in April of both years. In July of both years, Kodaikanal shows a clear bite-out with a higher afternoon peak while no such feature is seen at Huancayo. In January, it is difficult to make comparisons as Huancayo shows bite-out in 1964, and Kodaikanal shows bite-out in 1961. In 1964, $N_{max}\ F_2$ is lower than in 1961 in all seasons as can be seen from the scale.

(b) Comparison of constant electron density contours.

The height variations of constant electron density contours on Quiet days are shown in Fig. 2.13(Pg 58 (a)) for two equatorial stations. The comparisons are made season wise for 1964, a low sunspot year. The main features which emerge are:-

1) While Kodaikanal attains highest electron densities in the equinoxes (noon peak value is 12 x 10^5 el/cm^3), Huancayo seems to attain it in local summer, the noon

peak being (10×10^5) el/cm^3. It may be seen that the general shape of the contours of Kodaikanal equinox and Huancayo summer is rather similar. The presence of the forenoon and afternoon peaks is clearly seen in both, and the differences in these are as follows:-

1964

Month	Forenoon peak in el/cm^3	
	Kodaikanal	Huancayo
January	-	6×10^5
April	6×10^5	7×10^5
July	4×10^5	4×10^5

Month	Afternoon peak in el./cm^3	
	Kodaikanal	Huancayo
January	7×10^5	11×10^5
April	12×10^5	8×10^5
July	7×10^5	5×10^5

2) Though it is the local seasons of the two stations which have been compared, there is a greater resemblance between the July contours at the two stations. Huancayo January contours too certainly resemble Kodaikanal

58(a)

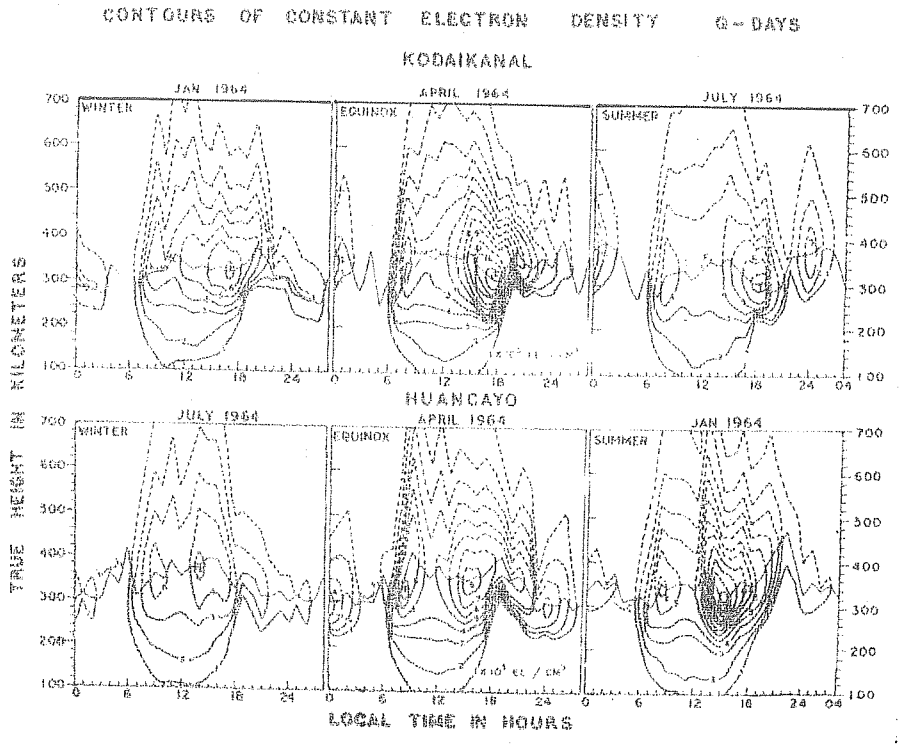


FIG 2.13

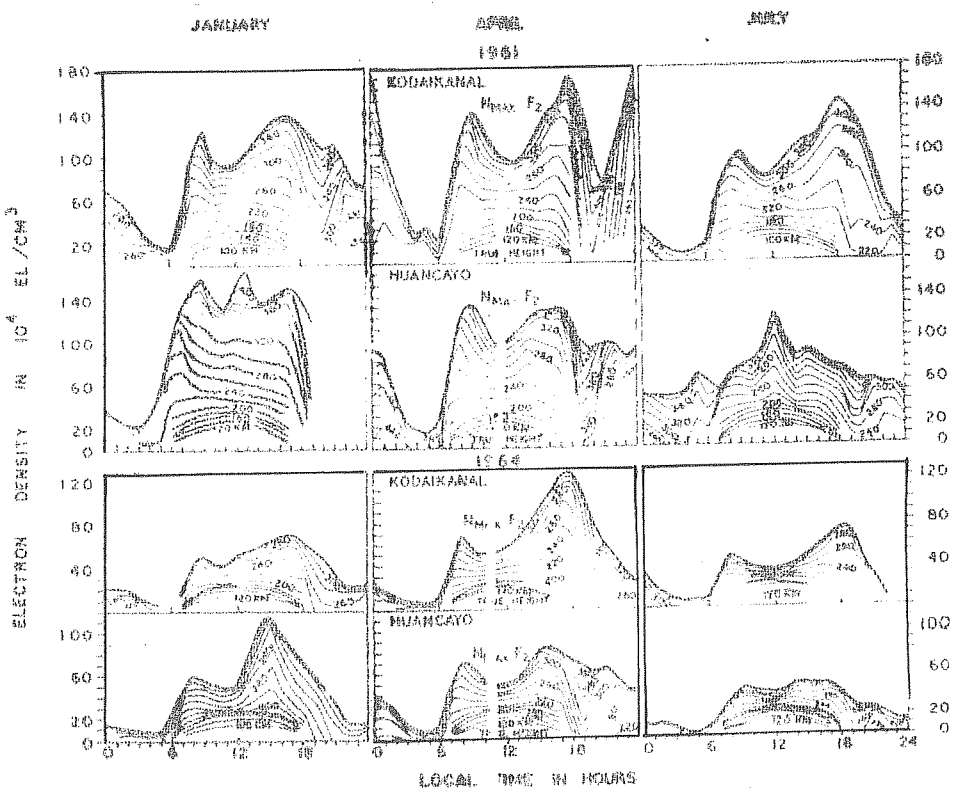


FIG - 2.14

January more than Kodaikanal July. Evidently at equatorial stations as is to be expected, seasonal changes play a smaller part in electron density distributions than solar zenith angle changes. Thus January behaviour at the two stations is similar, and differs from the July behaviour. The overall density of the contour lines is far less in July than in January, and the absolute electron densities are certainly less at Kodaikanal.

3) In all seasons, at both stations, the most rapid changes in electron density with height occur at around sunrise and sunset hours (06 hr. and 18 hr.) This seems more true of heights between the $h_{max}\ F_2$ level and 200 km where there is the largest crowding together of the contour lines; the effect again appears to become less with increasing height. It is greatest in the equinoctial months possibly because of the overhead position of the sun.

(c) Comparison of electron density distributions at constant heights.

Comparisons between the two stations are made for the January, April, and July months of 1961 (medium sunspot) and 1964 (low sunspot) in Fig. 2.14 (Pg 58 (a)). In 1961 the $N_{max}\ F_2$ shapes differ greatly between the two stations; there is sometimes a third peak at Huancayo at midday, notably in January and July. The sharp gradients in electron density at sunrise and sunset are seen more in

January and April months than in July. It is also seen that the midday bite-out feature commences at levels above 200 km. At both stations the bite-out is clearest in the equinoctial months.

A study of the solar cycle and seasonal variations in the F-region over Kodaikanal has been made by Ganesh (1965) by using true height electron density profiles obtained by the 10-point method of Schmerling and Ventrice. His studies support the observations made here of

(1) Solar activity effects manifesting themselves more at the higher F levels, with little or no change at the E and F_1 levels.

(2) Little or no change in y_m from low to high sunspot in summer (July), but considerable change in winter (January), the larger change occurring in the afternoon hours.

Ganesh has also made a comparison of electron density profiles for winter noon at Kodaikanal and Huancayo. He finds that the peak density in the South American zone is generally smaller than in the Indian zone. This does not quite tally with the results observed in this study.

CHAPTER III

METHODS OF ANALYSES OF F-REGION DISTURBANCES AND GENERAL REVIEW

3.1 Introduction

The world-wide characteristics of upper atmospheric storms are obtained from a synoptic study of local observations at different locations on the globe. Such observations may include variations in geomagnetic field and electron density distributions, occurrence of spread-F and sporadic E, visual aurora and red arcs, airglow, and radio absorption. With the advent of methods for topside probing, variations in ionic composition, electron and ion density, and temperature in the higher regions have also been observed.

The disturbed value of a geophysical parameter X is defined as

$$\Delta X = X(\text{obs}) - X(q) \quad \text{where}$$

X_{obs} is the observed value of X during a disturbance

X_q is the quiet day value of X which includes the regular S_q and L variations.

Following Chapman's (1936) method for the study of the geomagnetic field components, a widely-used method for studying a disturbed parameter ΔX is to classify it into two parts -

1) The D_{st} storm-time variation which is the average value of ΔX around a circle of constant latitude.

2) The DS disturbance local-time inequality or the SD solar daily disturbance.

The deviation ΔX is thus a function of geomagnetic latitude λ, the geographic longitude θ, and storm-time τ, and can be written as $\Delta X\ (\lambda, \theta, \tau)$. It is a component of the disturbance field D which can be written as

$$D = D_{st} + DS \qquad \overline{D} = D_{st} + SD$$

in which $\overline{D}$ is the average of D over 24 hours. D_{st} being a function of λ, and τ, and independent of longitude, can be expressed as

$$D_{st}\ (\lambda, \tau) = \frac{1}{2\pi} \int_0^{2\pi} D(\lambda, \theta, \tau)\, d\theta$$

DS being a function of local time is expressed as

$$DS\ (\lambda, \theta, \tau) = D\ (\lambda, \theta, \tau) - D_{st}\ (\lambda, \tau)$$

When the parameter considered is the critical frequency of the F_2 layer, these components become $D_{st}(f_oF_2)$, DS (f_oF_2), and SD (f_oF_2) respectively.

(a) D_{st} (f_oF_2) studies

Storm-time variations are computed by taking the hour

nearest to the time of sudden commencement of a magnetic storm (as deduced from magnetic records) as the zero-hour, irrespective of its local hour value. The value of f_oF_2 at this hour divided by the monthly median value of f_oF_2 for the same hour, gives the ratio f_oF_2 (storm)/f_oF_2 (median) This ratio is an estimate of the percentage change in f_oF_2 for that hour, because

$$\frac{f_oF_2 \text{ (storm)} - f_oF_2 \text{ (median)}}{f_oF_2 \text{ (median)}} = \frac{f_oF_2 \text{ (storm)}}{f_oF_2 \text{(median)}} - 1$$

Some workers have simply used the quantity f_oF_2 (storm) minus f_oF_2 (median) as an estimate of the degree of disturbance, but it is better to divide it by f_oF_2 (median), as then the dependence of disturbance on local time is also taken into account, and eliminated. The ratio f_oF_2 (storm)/ f_oF_2 (median) is written down for each of the hours following the zero-hour of the storm (these may be 48, 72 or 96 hours as required), and if so desired, for a few hours before the zero-hour of the storm, to obtain control day behaviour. When plotted, these values give the storm-time variation of f_oF_2 for the particular storm.

If the statistical behaviour of a large number of storms is required, the ratios for say the 72 hours following the zero-hour for each storm are written out on consecutive lines, with the zero-hour ratios lying one

below the other. The average of each column is then taken, and the 72 values thus obtained, represent the storm-time variation of f_oF_2 for the particular group of storms. This variation is independent of local time, as it is assumed that there is a uniform distribution of the hours of storm-commencement over all hours of the day. In reality however, some amount of diurnal component remains in the storm-time variation.

(b) DS (f_oF_2)- disturbance local time inequality

The DS (f_oF_2) for the same group of storms is computed by re-arranging the above data in a different way. The final row of 72 average ratios is written below the 72 values for each individual storm, and the difference for each column is taken. If the storm considered starts at 06 hr. local time, then the first 24 differences obtained correspond to the local times 06 hr. through 00 hr. to 05 hr., the next 24 differences correspond to the next 06 hr. through 00 hr. to 05 hr., and so on.

Each set of 72 differences is now in terms of local time, beginning at the hour of commencement of the individual storm considered. They are written in consecutive rows starting from the column containing the appropriate local time. The average of each column is obtained. The first 24 values represent DS (1) which is

the disturbance local time inequality for the first day of the group of storms, the next 24 values represent DS (2), the same parameter for the second day of storms, and so on.

This DS component depends on local time, and can be regarded as constant in form and position (but not in intensity) as viewed from the sun.

(c) SD (f_oF_2) - solar daily disturbance

SD (f_oF_2) does not differ much from DS (f_oF_2)save in the method of computation. Based on the K_p magnetic index values of the different days, the IAGA publishes the dates of the 5 quietest days of the month (the International Quiet Days denoted by Q) and of the 5 most disturbed days of the month (the International Disturbed Days denoted by D). The hourly values of f_oF_2 averaged for the 5Q days are denoted by S_q (f_oF_2) and the hourly values of f_oF_2 averaged for the 5D days are denoted by S_d (f_oF_2) .

The solar daily disturbance variation SD (f_oF_2) (also called disturbance daily variation) is then given as

$$SD\ (f_oF_2) = S_d\ (f_oF_2) - S_q\ (f_oF_2)$$

It consists of 24 hourly values ranging from 00 hr. to 24 hr. and is clearly a function of local time.

(d) N-h studies - Electron density distributions at true heights.

The above methods of computing D_{st} (f_oF_2) and DS (f_oF_2) are applied to groups of storms. Instead of such statistical studies, some workers study the detailed characteristics of individual storms (Somayajulu 1963, Matsushita 1963). This approach leads to essentially similar conclusions in most cases, and the separation into D_{st} and SD components can be made just as clearly. Each storm, however, has its own individuality and characteristics, and it is seldom that any two storms resemble each other exactly.

f_oF_2 studies refer only to changes in N_{max} F_2 the peak electron density. During a storm, there are significant changes in the altitude-distribution of F_2 region ionisation, and in the earlier days, these were studied through the variation of the virtual height of reflection of ionosonde echoes. The method was rather unsatisfactory, as the virtual height is strongly influenced by group - retardation of the sounding pulses, in the lower ionospheric regions lying below the F_2 peak.

The computation of electron densities at true heights from ionograms is done by either Model or Integral methods,(Ratcliffe 1951; Schmerling 1958; Budden 1954;

Thomas and Vickers 1958) and is a long and complicated process. Recently, the development of electronic computer techniques for true-height analysis of ionograms has quickened and simplified such computations, and has helped in the investigation of changes in the altitude-distribution of electron densities during storms. Such analyses confirm that during storms, large changes in electron density do occur, especially above heights of 180 km - 200 km.

3.2 Review of earlier work on the bottomside F-region

The earliest reports of geomagnetic storm effects on the F-region were made by Appleton and Ingram (1935) when they found that at high-latitude stations Slough and Tromso, f_oF_2 was reduced. Berkner et al., (1939), and Berkner and Seaton (1940), found that for an equatorial station Huancayo, the opposite was observed, the effect of storms being to increase f_oF_2. Martyn (1953 b) from a study of mid-latitude stations Washington, Canberra, and Watheroo, found that storms generally had the effect of depressing f_oF_2 in summer and the equinoxes, but the effect was much smaller in winter; in fact f_oF_2 seemed to be slightly increased in winter. Other workers have shown this seasonal variation of F-region storm-effects (Rastogi 1962, Skinner and Wright 1955) by correlating the variation of $(f_oF_2)^2$ i.e. $N_{max}F_2$ with K_p index for summer and winter separately. F_2 layer disturbances seem to lag behind magnetic disturbances by the order of a day (J.W. King, 1961).

Systematic morphological studies of F-region disturbances were made by Appleton and Piggott (1952), Martyn (1955), Obayashi (1952, 1954, 1959) and others. A detailed study of ionospheric disturbances for Canadian stations was done by Meek (1952). Matsushita (1959), studied D_{st} (f_oF_2) for 109 storms at 38 observatories situated all over the world, by grouping them into eight geomagnetic latitude zones, and classifying the storms into strong and weak ones. These results are shown in Fig. 3.1 (Pg. 68 (a)) and they confirm the general characteristics obtained by earlier workers.

1) In high latitudes, a marked depression of f_oF_2 is seen during storms. The largest effect is centred near the auroral zone, and it has a pronounced diurnal variation.

2) In equatorial and low latitudes there is generally an increase of f_oF_2 accompanying a storm. A depression of f_oF_2 is a rare occurrence, which happens only during a very severe storm.

3) At mid-latitudes, a decrease of f_oF_2 is definitely observed during summer and equinoxes, but in winter there is occasionally an increase of f_oF_2 .

The local time of commencement of a storm is found to have an effect on the behaviour exhibited by f_oF_2 (Appleton and Piggott 1952). For mid-latitudes,

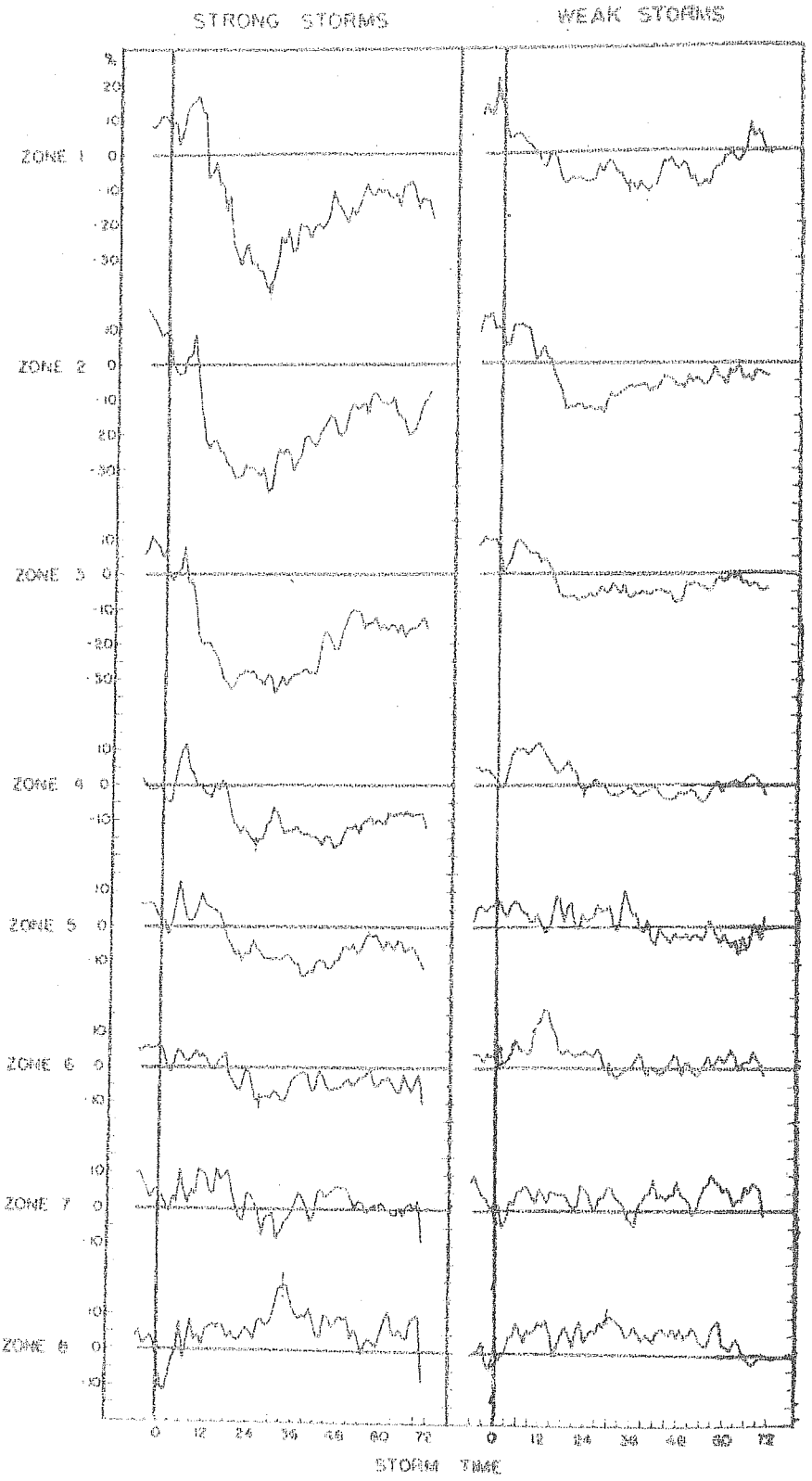


Fig. 3.1 D_{st} ($N_M F_2$) variations for strong and weak storms for the geomagnetic latitude zones
(1) 60° - 55° (2) 55° - 50° (3) 50° - 45° (4) 45°-40°
(5) 40° - 30° (6) 30°-20° (7) 20° - 10° (8) 10° to (-10°)
(Matsushita 1959).

Thomas and Venables (1966) find that the major changes in f_oF_2, depend on the local time of the main phase of the magnetic storm; if this be in the night hours, f_oF_2 shows an immediate depression, but for a daytime main phase, this sudden drop in f_oF_2 is not seen.

One of the storm-effects seen in ionograms is the visibility of a clear F_1 ' cusp ', often at times when it is not normally seen. This is believed to be an increase of the parameter.

$$G = \frac{\beta^2}{\alpha q}$$

where β - attachment coefficient

α - recombination coefficient

and q - production rate

This is probably due to an increase in the loss coefficient β, and G.A.M. King (1962 a; 1967) finds that G generally increases when the magnetic disturbance figure K increases.

During storms the h'F curves of the F_2 layer are greatly changed, and the great increase in virtual height, often up to 600 km was previously considered to be real. With the increasing use of techniques for true height reduction of ionograms, it is becoming increasingly clear

(Thomas and Robbins 1958; Becker 1964) that these fantastic increases of virtual height are due to group retardation of the probing radio waves in the lower ionospheric layers, and that the changes in storm-time $h_{max} F_2$ depart by only $\pm$ 30 km from quiet days.

Matsushita (1963) and Somayajulu (1963) have analysed the storm-effects at several American stations by using hourly N-h data. Their main conclusions are:

1) Most changes in N-h distribution occur in the region above 180 km in summer and the equinoxes, seldom below that. In winter the changes are predominant above 300 km.

2) The sub-peak total electron content N_T behaves in the same way as $f_o F_2$.

3) The peak height of the F_2 layer ($h_{max} F_2$) and its semi-thickness ($y_m F_2$) generally increase during a storm both in summer and in winter, though an occasional decrease occurs in winter.

It is believed that the electromagnetic radiations during a solar flare do not affect the F-region as much as the corpuscular radiation or storm effects, but a few isolated cases of photon effects have been noted on the F-region. Sato (1957 b) and Brown and Wynne (1967) found a reduction

of about 10% in N_mF_1 following a flare. Dieminger et al.,(1950) reported such a case for Lindau on November 19, 1949; Shapley and Knecht for Okinawa, and Bhargava and Subrahmanyan(1962)for Kodaikanal on February 23, 1956, and Knecht and McDufffe on November 12th, 15th, 1960. The height of the F_2 peak in all these cases was below a critical height i.e. below 300 km. It is interesting to note that all these cases occurred in the local winter months. Kotadia (1966) pointed out that daytime solar flares caused a marked increase in f_oF_2 in winter.

Artifical nuclear explosions have offered another means of studying disturbances in the F-region (Kotadia 1967). The tests in the Pacific, and at Novaya Zemlya showed the effect of travelling pressure waves on the F-region (Obayashi 1962; Oksman and Kataja 1962). The pressure wave caused an anomalously large increase in electron density followed by fluctuations of the same, as it moved from near to distant stations with an average speed of 400m/sec.

3.3 Review of topside studies of the F-region

The topside is the name given to that part of the ionosphere which lies above the $h_{max}F_2$ level. Till 1958, ground-based ionosondes had supplied most of the world-wide electron density data, while rocket measurements had yielded most of the information about ionic composition, plasma temperatures, and ionising radiations, all upto the

level of $h_{max}F_2$. The advent of satellites and other methods of directly probing the higher regions of the ionosphere since the IGY, has led to much progress in our knowledge of the topside on a world-wide basis.

(a) Methods of probing the topside ionosphere

A large variety of 'in situ' experiments can be put aboard a satellite, and these relay direct measurements of the parameters concerned, to ground.

The incoherent back-scatter radar technique is another way of studying the topside as well as the bottom-side. It is capable of estimating ionisation densities and temperatures throughout the ionosphere to heights of over 1000 km. Its working principle is that the total power scattered back by electrons in a pulse volume at a particular height is proportional to the number of electrons in that volume. The characteristic width of the spectrum observed depends on the ratio T_e/T_i where T_e is electron temperature, and T_i is ion temperature.

Three stations exist in the 70°W longitude region - Jicamarca at equatorial latitudes, Arecibo at 30°N, and Millstone Hill at 55°N. Three others are Prince Albert in Canada, Nancay in France, and Malvern in England. These six stations have yielded valuable information on the

time-variations of electron and ion densities, and temperatures.

Faraday rotation and Doppler shift of signals reflected from satellites or the moon (Klobuchar et al., 1964) and Whistler studies (Carpenter 1966) are two other methods of inferring electron densities in the topside.

(b) The topside during Quiet conditions

The main ionic constituents in the topside are O^+, He^+, H^+ and a small amount of N^+. The gases separate out under diffusive equilibrium, according to their atomic weights, with the heavier nitrogen and oxygen below, then helium to form the heliosphere, and hydrogen above to form the protonosphere. Their relative concentrations depend on altitude, latitude, local time, season, and level of solar activity. Under conditions of sunspot minimum, He^+ is found to be a minor constituent (less than 30%) at all times (Carlson and Gordon 1966) with its maximum occurrence around 500 km by night, and around 1000 km by day. The transition from O^+ to predominently H^+ occurs around 700 km at night, and 900 km by day (Gordon 1966). As in the lower ionosphere, sudden and rapid changes occur in the topside at sunrise and sunset. Satellite studies show that above 800 km at night, a deep equatorial trough in He^+ is formed with a corresponding rise in O^+, possibly arising from the charge-exchange

processes of N_2, O_2 and O with He^+ (Chandra et al., 1970; Dalgarno 1964, Maier 1968):

In the height range of about 500 km, the geomagnetic anomaly shows up in the daytime latitudinal variation of O^+, with maxima occurring at $\pm$ 20° geomagnetic latitude (Chandra and Goldberg 1964; Hanson and Moffett 1966). This is again an instance of geomagnetic and gravitational effects on ionospheric plasma.

Satellite and back-scatter studies have yielded useful information on ion temperature (T_i), electron temperature (T_e), and neutral temperature (T_n) in the higher regions. In the daytime T_i increases from around 1000°K near the F_2 peak (about 400 km.) to a few thousand degrees Kelvin at about 800 km and remains isothermal to beyond 1000 km. Night-time values are almost half the daytime ones. $T_e \approx 3\ T_i$ near the F_2 peak, but approaches T_i at greater heights. The daytime pattern seems fairly stable with time, but the night-time pattern seems to vary. Seasonal changes are not marked (Gordon 1966). Both T_e and T_i increase polewards from the equator, with maxima between 40° and 50° geomagnetic latitude (Brace et al., 1967).

(c) <u>The topside during disturbed conditions</u>

Studies of the topside show that magnetic disturbances can cause changes in the following parameters:

a) T_e and T_i , and neutral temperature and density

b) concentration of different ionic species

c) spatial distribution of electron density

All these vary with altitude, latitude, local time, and storm-time, and often the large changes in the topside do not manifest themselves at the level of $h_{max} F_2$. Very often too, results of the topside obtained by different methods do not tally. A good review of the topside during geomagnetic storms has been given by Warren (1969) .

Studies of air-drag force on satellites show that the neutral air density increases with magnetic disturbance , and is strongly latitude - dependent, being especially high at high latitudes (Jacchia 1961; Newton et al., 1965; Schilling and Whitney 1959). Groves (1961) expressed the variation of neutral density with K_p as

$$\rho = \rho_0 (1 + \alpha K_p)$$

with α = 0.2 for low latitudes

and α = 0.6 for high latitudes

Thomson scatter studies at Millstone Hill, Arecibo, and Prince Albert, show in general that not taking diurnal variations into account:

T_e (disturbed) $>$ T_e (quiet) by 300°K to 600°K but T_i (disturbed) $>$ T_i (quiet) by less (Evans 1965; Rao 1968)

Topside sounder studies agree with backscatter radar results on temperatures, and an increase of 4% in temperature per unit increase of K_p was observed (Watt 1966). Jacchia (1964) showed that the effect of magnetic storms on temperature can be expressed as

$$\triangle T = 1.2\ a_p\ ^{\circ}K$$

where a_p - 3-hour geomagnetic planetary index
$\triangle T$ - change in temperature

Direct studies by satellite - borne probes however give different results. Willmore (1965) using the Langmuir probe on Aeriel I, invariably found a decrease in T_e during disturbances both by day and night. Reddy et al., (1967) too found similar results for the mid-latitudes from their electrostatic probe on Tiros VII. Both of them found an increase in N_e occurring simultaneously with a drop in T_e.

Mariner II results (Coleman et al., 1962) showed that both electron density and magnetic field intensity in the topside increase during the initial phase of a storm. Explorer 26 (Cahill et al., 1966) found that the particles responsible for the main phase appeared over the equator

between L = 2 and L = 6 in the late noon and evening latitudes. Gledhill et al., (1967) found a strong correlation between particle precipitation near the magnetic shell L = 4 and the occurrence of ionospheric disturbances. Whistler studies by Carpenter (1963) showed that the "knee" in electron density moved to lower L values with increasing K_p, indicating that N_e at very high altitudes decreases.

From Faraday rotation studies of radio signals reflected from the moon, Klobuchar et al., (1964) found that the total electron content N_T on a disturbed day was only half that on a quiet day. Millman (1964) reflected radio signals from the satellite Echo I, to find that while N_T increased with K_p by day, it did not do so at night. Hibberd and Ross (1967) used the differential Doppler technique on radio transmissions from Transit IV-A to find that at mid-latitudes, the slab-thickness on storm days was larger than on a quiet day. Titheridge and Andrews (1967) found that the scale height gradient dH/dh increased greatly during the positive phase of a storm, then sharply decreased. This decrease in dH/dh was interpreted as an increase in the transition height at which O^+ is replaced by lighter ions. Watt (1966) could not obtain any correlation between scale height and K_p by day, but at night the $O^+ - H^+$ transition - level rose at the rate of 30 km/unit increase of K_p.

To summarise topside results:

At the equator

King et al., (1967) found that levels near N_{max} F_2 are more sensitive to storm changes than higher levels. In the topside too, the equatorial anomaly vanishes during disturbances.

At mid-latitudes

For very severe storms - both N_T, N_{max} F_2 decrease
For moderate storms - $N_{max}F_2$ decreases but N_T increases
For mild disturbances - N_T increases but T_e decreases.

At polar latitudes

Nishida (1967) finds amidst irregularities, certain features of permanence in topside electron density such as

1. The polar peak
2. the auroral peak
3. the mid -latitude trough and evening increase of ionisation. Storms are found to enhance the peaks and deepen the troughs. Above 500 km. both N_e and T_e increase (Ondoh 1967, Reddy et al., 1967).

Topside studies have decisively shown that the depression phase of F-region storms at middle and high latitudes represents an actual decrease in the total number of electrons in the ionosphere, and is not due to a mere spatial re-distribution of the ionisation present.

CHAPTER - IV

STUDIES OF THE DISTURBED F-REGION

4.1 Introduction

F-region disturbances manifest themselves differently at the different latitudes of the earth as has been shown by earlier workers. Most references of their work have been given in Ch. 3. Here the disturbance effects are shown by choosing an equatorial station and an example each in the northern and southern hemispheres, of a low-latitude, a mid-latitude, and a high-latitude station. Such a network of stations is selected for the East and the West zone separately so that longitudinal differences if any, are also shown.

It is known that the equatorial anomaly in f_oF_2 occurs between $\pm$ 35° magnetic dip and high latitude phenomena like aurora occur around 67° dip. Hence in the present analysis the latitude zone of a station is classified on the basis of its dip thus

LATITUDE ZONE	RANGE OF DIP ANGLE
Equatorial	0° - 10°
Low-Latitude	10° - 35°
Mid-Latitude	35° - 70°
High-Latitude	70° and above

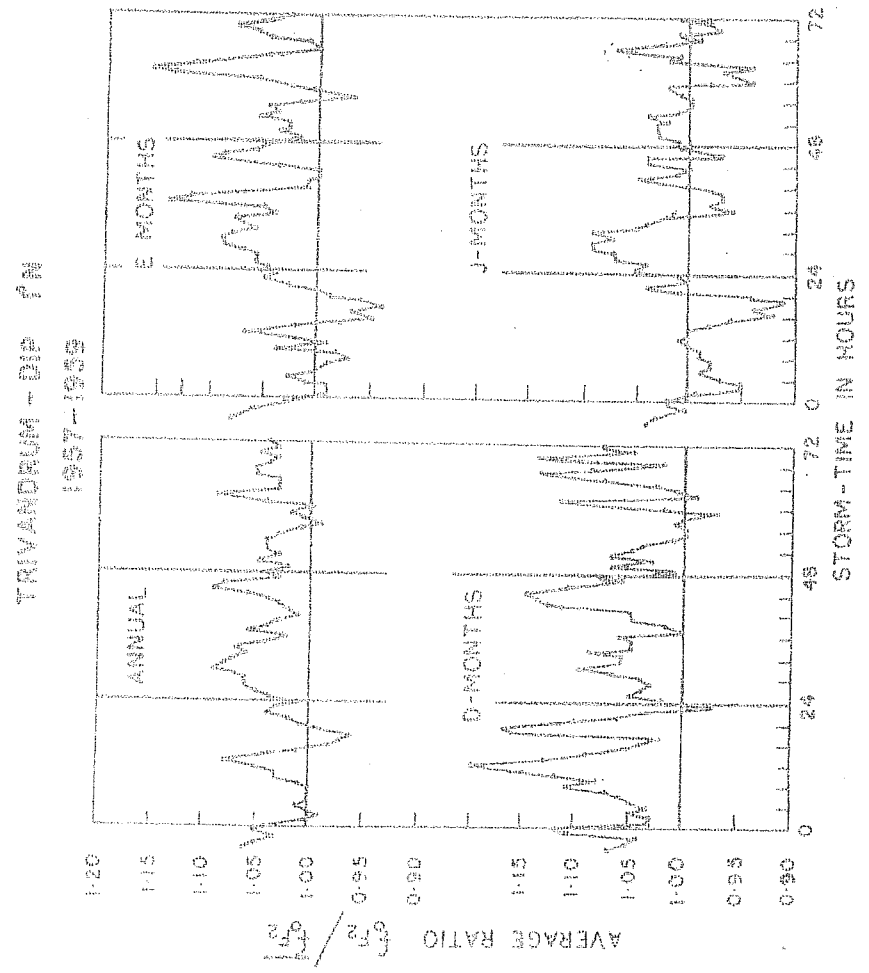
Disturbance storm-time variations of f_oF_2 D_{st} (f_oF_2)

These studies use the method of analysis described in Section 3.1(a) of Chapter III. The time of storm commencement is taken as zero-time, and the ratios are computed for the period 4 hours before the commencement, to 72 hours after commencement of the storm. The period considered is IGY-IGC (1957-1959) and the total number of storms considered is over 100 for each station. Of these, about 40 storms occurred in the equinoxes, and about 30 each during the solstices. The storms are all strong ones with Ap exceeding 100 on any one of the 3 days following the storm.

4.2 Seasonal D_{st}(f_oF_2) variations at equatorial, low, mid, and high latitudes.

(1) Equatorial stations:

Fig. 4.1 (Pg. 80 (a) shows the seasonal behaviour of D_{st} (f_oF_2) at Huancayo in the West, and Trivandrum in the East zone. The ordinate is the average ratio f_oF_2 storm/ $\overline{f_oF_2}$ for all the storms and the abscissa is the storm-time in hours. Some longitudinal differences in the variations are seen. The Annual variation is a 'positive' one in both cases (i.e. the ratio exceeds 1.00, implying disturbed f_oF_2 values are larger than the median f_oF_2).While the general pattern is the same, the recovery time seems longer for Trivandrum, the ratio not having returned to 1.00 even 72 hours after storm-commencement. In the


TRIVANDRUM - 2558 - 1958
ANNUAL
6-MONTHS
3-MONTHS
1-MONTHS
AVERAGE RATIO $\bar{G}_{r2}/\bar{G}_{r1}$
STORM-TIME IN HOURS

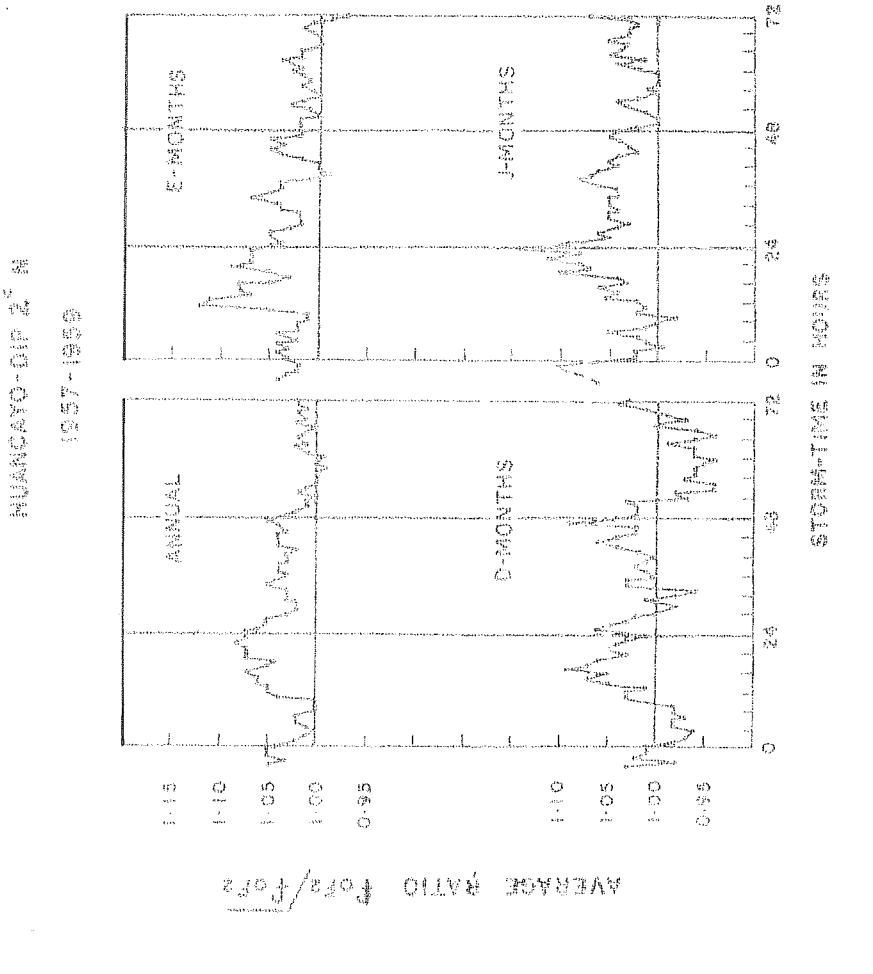

BANGALORE - 2015 - 1957 - 1965
ANNUAL
6-MONTHS
3-MONTHS
1-MONTHS
AVERAGE RATIO f_{0r2}/f_{0r1}
STORM-TIME IN HOURS

Fig. 4.1

E-months too, the variations at both stations are positive; but at Huancayo while ratios on the 3rd day are of small magnitude, at Trivandrum they are still fairly large. In the D-months, Huancayo shows some 'negative' phase (i.e. the ratio $f_oF_2 / \overline{f_oF_2}$ is less than 1.00, implying that disturbed f_oF_2 values are less than the median f_oF_2). At Trivandrum there is a completely positive phase. In the J-months, the variation at Huancayo is completely positive, in keeping with its winter conditions while Trivandrum experiences negative phase in its summer conditions. It may be noted that though both these stations are equatorial from the point of view of magnetic dip, Huancayo has a geographic latitude of 12^oS and is experiencing summer while Trivandrum with a geographic latitude of 10^oN is having winter. The differing D_{st} (f_oF_2) variations at these two stations may thus be a seasonal effect. The ratio-fluctuations at Trivandrum seem to be more than those at Huancayo.

(2) Low-latitude stations

We now compare Talara with a dip of 13^oN and Tucuman with a dip of 22^oS, both lying in the West zone, with Baguio (dip 19^oN) and Singapore (dip 17^oS) both lying in the East zone (Fig. 4.2) (Pg. 81 (a)). Such depiction also enables us to sort out asymmetry between the northern and southern hemisphere if any exists.

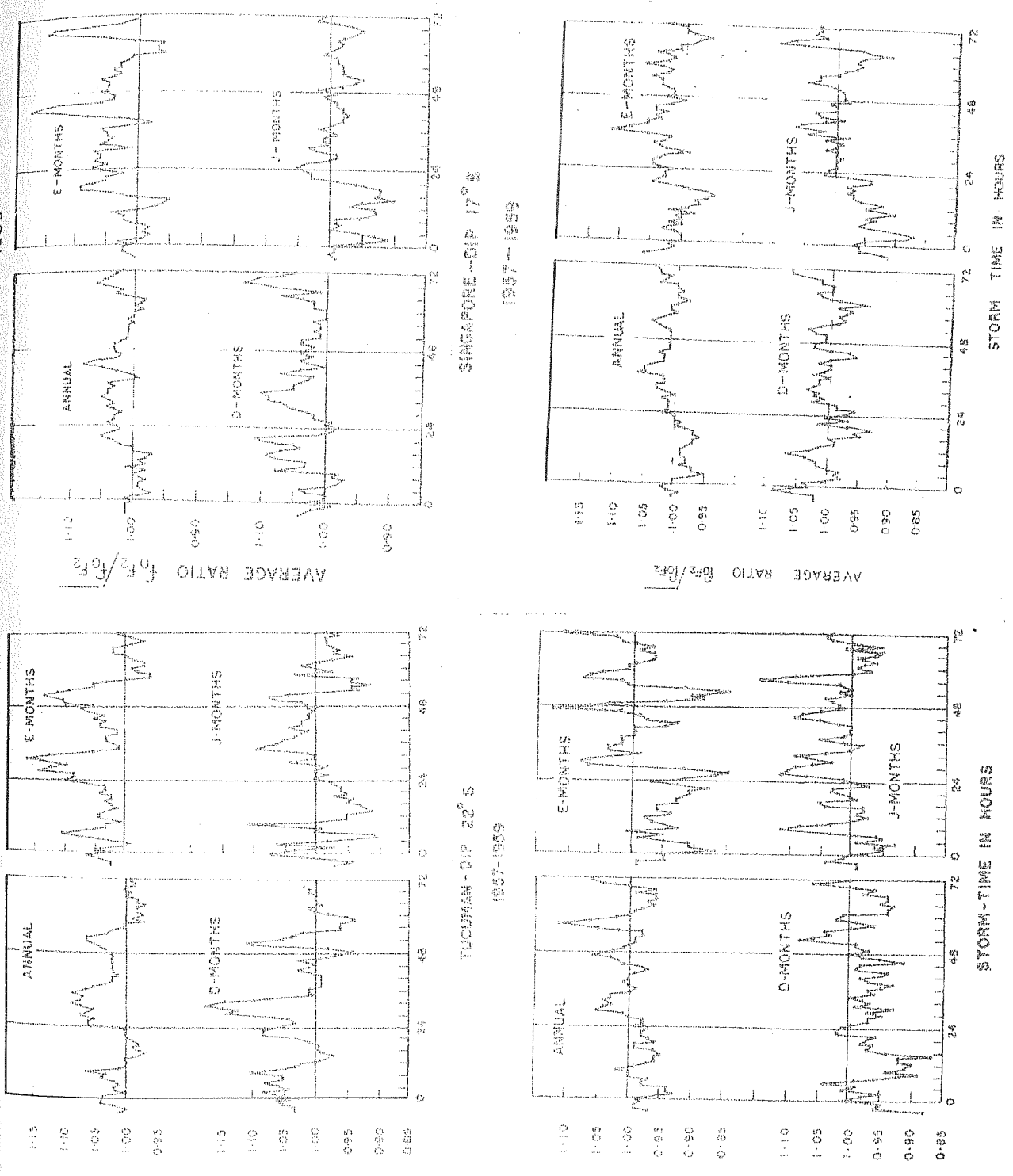

ANNUAL
D-MONTHS
E-MONTHS
J-MONTHS
AVERAGE RATIO f_{0E}/f_{0E_2}
AVERAGE RATIO f_{0E_2}/f_{0E}
STORM TIME IN HOURS
SINGAPORE - DIP 17°S
1957 - 1959
TUCUMAN - DIP 22°S
1957 - 1959

FIG 4.2

The annual and E-month variations at Talara and Bagiuo are both positive. In the D-months too, the variations at both stations are mainly positive. In the J-months more of a negative phase exists but both stations have some positive phase on the second day of the storm. The general behaviour at the two stations is not vastly different.

Now consider the southern hemisphere stations Tucuman, and Singapore. The Annual variations are negative on the first day, but positive on the second and third days. The E-months show a chiefly positive variation at Singapore, but at Tucuman, it is negative. In the D-months, the variation at Singapore is uncertain, but at Tucuman it is mostly negative. In the J-months, Tucuman shows a positive trend, whereas Singapore shows a positive trend only on the second day. A good amount of longitudinal difference is seen between these two stations, though geographically they experience the same seasons.

Comparing Baguio and Singapore in the East zone for north-south asymmetry, the Annual and E-month variations are alike at both stations. To obtain similar seasonal conditions, the D-month behaviour at Baguio has to be compared with the J-month behaviour at Singapore when 'winter' prevails. Despite the almost equal dip values of the stations, the winter D_{st} (f_oF_2) behaviour is by no means alike, there being practically no negative phase at

Baguio, but a considerable amount of negative phase at Singapore. For local summer, the J-months at Baguio would compare with the D-months at Singapore. Here the variation of D_{st} (f_oF_2) differs only in the first few hours of the storm.

In the West zone, even the Annual and E-month behaviour at Talara and Tucuman differ, but this could be because of the fairly different dip values of the two stations.

(3) Mid-latitude stations

We now compare Puerto Rico (dip 51°N) and Port Stanley (dip 46°S) in the West zone with Akita (dip 53°N) and Townsville (dip 48°S) in the East zone (fig. 4.3) (Pg. 83 (a))

It is interesting to compare the pair of mid-latitude stations, Puerto Rico (dip 51°N) and Akita (dip 53°N). The prominent feature about these is the small D_{st} (f_oF_2) variation shown in the Annual curve for both stations, the variation on the whole being a negative one. The E-month variation is clearly negative at Akita, and a similar type of variation is seen at Puerto Rico. In the D-months, both show a clear positive variation, while in the J-months both show a clear negative variation. Hardly any asymmetry in storm-behaviour exists between the two stations. It is

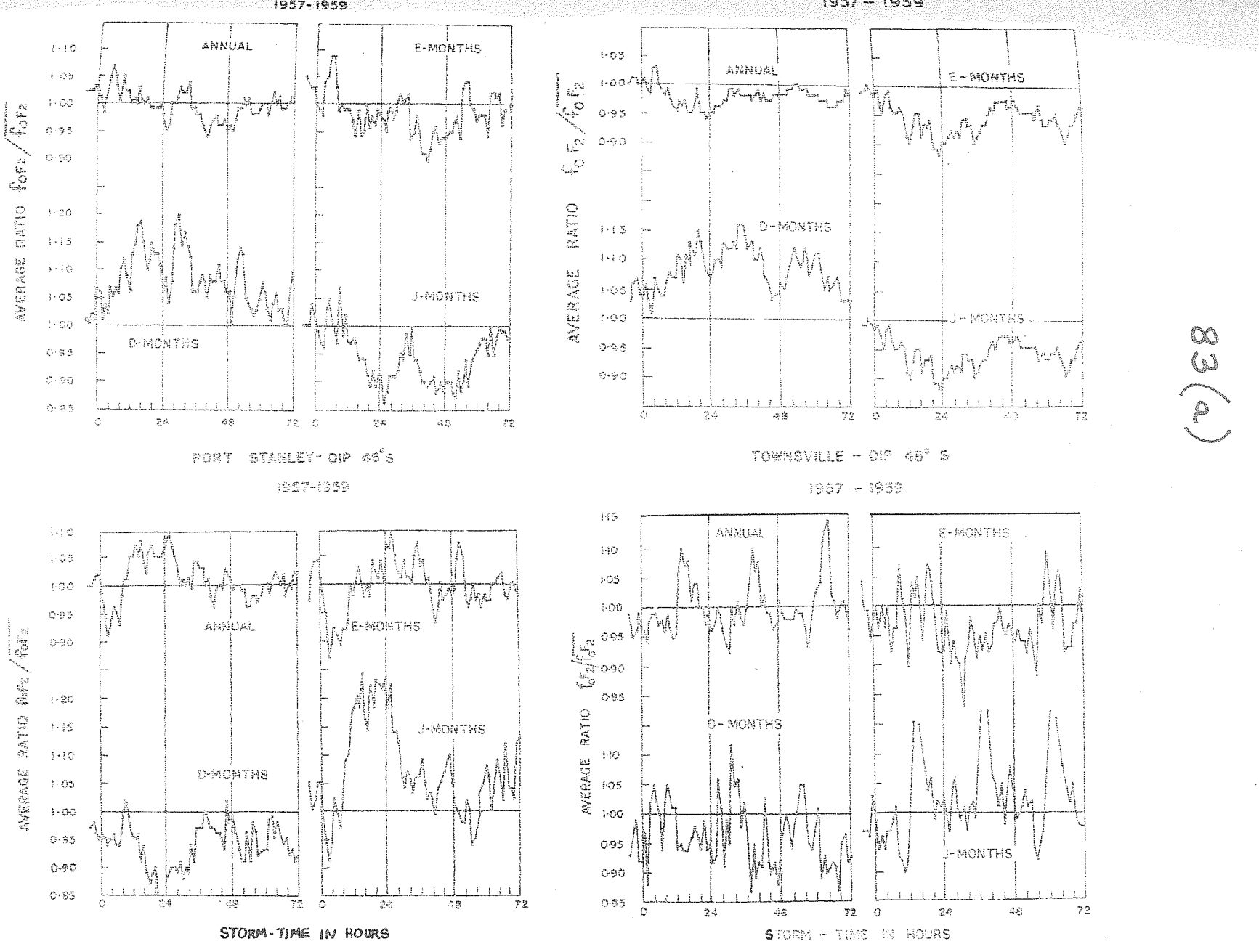

1957-1959
ANNUAL
E-MONTHS
D-MONTHS
J-MONTHS
AVERAGE RATIO $f_0F_2/\overline{f_0F_2}$
PORT STANLEY - DIP 46°S
1957-1959
TOWNSVILLE - DIP 65° S
1957 - 1959
STORM-TIME IN HOURS

FIG 4·3

(a) 83

interesting to speculate whether the small Annual D_{st} (f_oF_2) variations have anything to do with disturbed - time current foci locations in the two zones.

Comparing Port Stanley and Townsville, at Port Stanley the annual variation is clearly positive during the first 48 hours but at Townsville the variation is uncertain. In the E-months, the variation at Port Stanley is definitely positive, but at Townsville, it is clearly negative. In the D-months, the variation is negative at Stanley, and on the whole negative at Townsville. In the J-months Stanley shows a vastly positive variation with a peak value of 1.25; the variation at Townsville is less positive with pronounced 24 hour ratio peaks. Thus in spite of the similar dips of the two stations, a good amount of longitudinal asymmetry exists in the southern hemisphere.

Now we compare Puerto Rico and Port Stanley in the West zone for north-south asymmetry. While the Annual and E-month variations at Puerto Rico are negative, the variations at Stanley are decidedly positive. Local winter requires the comparison of the D-months at Puerto Rico with the J-months at Stanley; both show positive variations, but there is a slight difference in the pattern. For local summer conditions one compares the J-months at Puerto Rico with the D-months at Stanley. Both show a negative variation. There is not much north-south asymmetry in the solstices but the

asymmetry is marked in the E-months in the West zone.

We now compare Akita and Townsville in the East zone. The Annual and E-month variations are less negative at Townsville than at Akita. Local winter (D-months for Akita and J-months at Townsville) variations are positive at both places but a strong, 24-hour component is seen at Townsville. In local summer while the variation is a clear negative during the J-months at Akita, it is not so clear at Townsville in the D-months. Some amount of north-south asymmetry does exist in the East zone too.

(4) High-latitude stations

We now compare Resolute Bay (dip 89°N) and Pole Station (dip 75°S) in the West zone with Tixie Bay (dip 83°N) and Scott Base (dip 83°S) in the East zone (Fig.4.4) (Pg. 85 (a)).

The outstanding point about the D_{st} (f_oF_2)variations at all these stations is that they exhibit large and rapid fluctuations. This clearly has something to do with high-latitude conditions. The later models of the magnetosphere believe that the geomagnetic field lines at high latitudes are directly connected to the interplanetary magnetic field lines (Dungey 1961) and charged particles emitted from the sun during disturbed conditions have easy and direct access to these regions of the earth. These sharp fluctuations in

85(a)

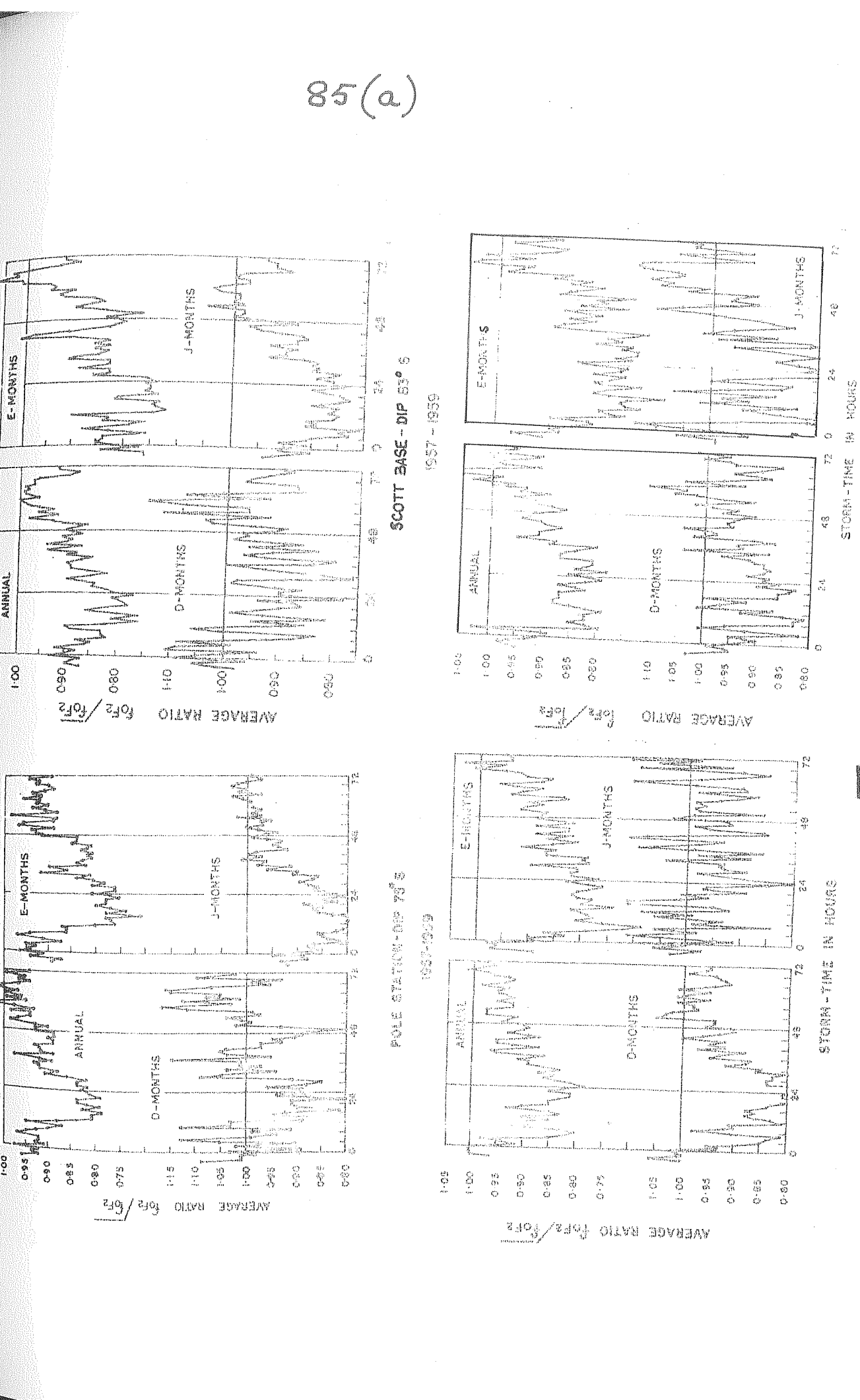

SCOTT BASE – DIP 83° S
1957 – 1959
POLE STATION – DIP 75° S
1957 – 1959
ANNUAL
D-MONTHS
E-MONTHS
J-MONTHS
AVERAGE RATIO f_{0F2}/f_{0F2}
STORM-TIME IN HOURS

Fig 4·4

(f_oF_2) behaviour may therefore be connected with these charged particles and the secondary ionisation they cause, each peak corresponding to a fresh quantum of ionisation. The overall behaviour of(f_oF_2) in spite of these peaks is a decrease during disturbed conditions. This may be due firstly, to the motion of field lines blowing ionospheric plasma into the tail of the magnetosphere (Banks and Holzer 1968) and secondly, to the enhanced recombination rates due to enhanced temperatures by corpuscular frictional heating and Joule current heating. These aspects are dealt with in detail in Chapter 7.

The overall variations of D_{st} (f_oF_2) at Resolute Bay and Tixie Bay compare closely in all seasons. The same may be said of Pole Station and Scott Base. Very little longitudinal variation exists at high latitudes. North-south asymmetry too does not exist greatly in either zone when one compares similar seasons (i.e. D-months in the north with J-months in the south and vice-versa).

4.3 North - south Asymmetry in storm-time variation of f_oF_2

From this study of D_{st} (f_oF_2) variations at equatorial, low-latitude, mid-latitude, and high-latitude stations, it seems as though north-south asymmetry in seasonal storm-time behaviour is most marked for mid-latitude, and little asymmetry exists for the other latitude zones.

A good deal of longitudinal difference does exist but this will be dealt with in Chapter 5. Some studies of ionospheric F_2 behaviour at conjugate places in low latitudes have been made by Matsushita (1968).

Here a detailed study of north-south storm-time asymmetry at middle latitudes was made by choosing suitable pairs of northern and southern stations in different longitude zones for low and high sunspot years. The behaviour for the low sunspot period (1951-1956) was studied for the Asian, African, American and Pacific zones, and is described in Paper (1) which follows. The high sunspot behaviour (1957-1961) was studied by using seasonal classification too, and the results are described in Paper (2).

The above-mentioned studies suggest that (1) North-south asymmetry is most marked in the American and Pacific mid-latitudes, and is less in the Asian and African zones. (2) In the American zone, the asymmetry is most prominent in the equinoxes; in the Pacific zone it is in local summer, while in the Asian zone it is in local winter.

(Papers 1 and 2 follow overleaf)

Paper 1

Journal of Atmospheric and Terrestrial Physics, 1968, Vol. 30, pp. 651–653. Pergamon Press. Printed in Northern Ireland

SHORT PAPER

North-South asymmetry in storm time variation of f_0F2

GIRIJA RAJARAM and R. G. RASTOGI
Physical Research Laboratory, Ahmedabad 9, India

(*Received* 2 *October* 1967)

Abstract—The study of Dst (f_oF2) variations at equatorial and subtropical stations at different longitude zones for 1951–1956, show that at equatorial stations of any in the zones the variation indicates an increase of f_oF2 during the main phase. The northern subtropical stations in any of the zones indicate a decrease of f_oF2 during the main phase. The southern subtropical stations show decreased f_oF2 for Asian and African zones but at American and Pacific zones an increase of f_oF2 during main phase of the storm is noted.

IT HAS been shown by earlier workers that the critical frequency of the $F2$-layer, f_0F2, at middle latitudes is reduced during the main phase of geomagnetic storms while at low latitudes there is an increase of f_0F2 in the corresponding period (APPLETON and INGRAM, 1935; BERKNER and SEATON, 1940; MARTYN, 1953; and SKINNER and WRIGHT, 1955). Averaging over a large number of stations, MATSUSHITA (1959) found that at middle latitudes, storm time variation of f_0F2 [i.e. Dst (f_0F2)] is characterised by an initial increase followed by much larger decrease while at equatorial regions the phase of variation is reversed. Comparing the equatorial anomaly of the $F2$-region of the ionosphere on quiet and disturbed days during the equinoxes of 1952, RASTOGI (1966) found that in the north subtropical region, f_0F2 was lower on disturbed than on quiet days, but in south subtropical region, f_0F2 was slightly greater on disturbed than on quiet days, suggesting some N–S asymmetry in the ionospheric storms.

The present paper describes the storm-time variation in f_0F2 at stations near the magnetic equator, and at northern and southern subtropical latitudes along approximately the same longitudes. The longitude zones are (1) Asian zone where the geographic and magnetic equators are almost parallel to each other (2) African zone where the geomagnetic and magnetic equators are most separated (3) American zone where the magnetic equator is shifted maximum southward and (4) Pacific zone where the magnetic equator crosses the geographic equator. In each of the zones except the Pacific zone there existed some equatorial as well as northern and southern subtropical stations during 1951–1956. For the Asian zone the data of the equatorial station Nhatrang (dip. 6°N) for the period January 1951–December 1955 were combined with the data at Kodaikanal (dip. 4°N) for the period (January 1956–December 1956). The behaviour of $F2$-region at these two stations has been found to be similar. As usual, the zero hour was taken as the hour nearest to the time of sudden commencement of a geomagnetic storm. Twenty-two strong SC storms were chosen in which in the succeeding 72 hr the maximum value of A_p index was greater than 50. The same storms were used for all the stations.

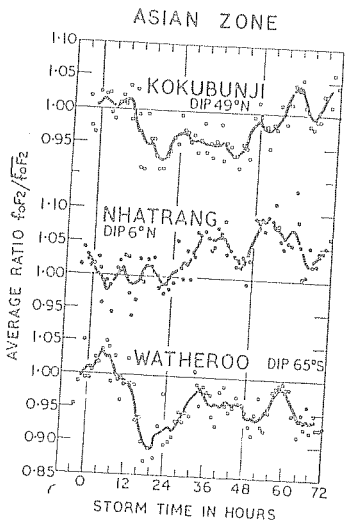


Fig. 1. Storm-time variation of f_oF2 at north subtropical, equatorial and south subtropical stations in the Asian zone.

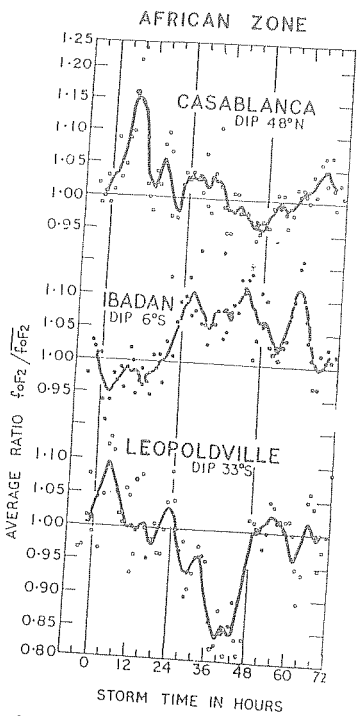


Fig. 2. Storm-time variation of f_oF2 at north subtropical, equatorial and south subtropical stations in the African zone.

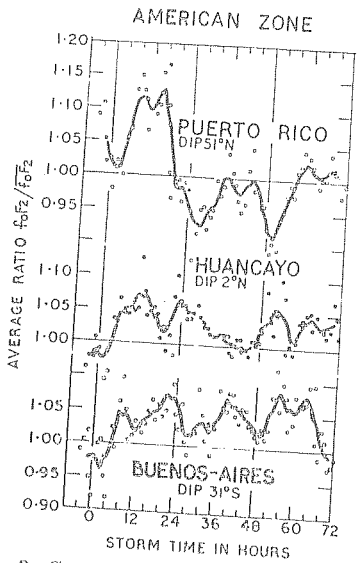


Fig. 3. Storm-time variation of f_oF2 at north subtropical, equatorial and south subtropical stations in the American zone.

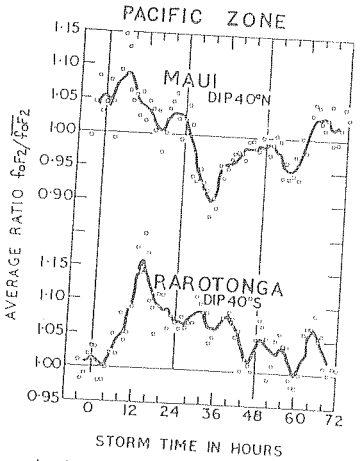


Fig. 4. Storm-time variation of f_oF2 at north subtropical, equatorial and south subtropical stations in the Pacific zone.

Figures 1, 2, 3 and 4 show the average storm-time variations at groups of stations in the Asian, African, American and Pacific zones respectively. The solid lines are the 5-hr running means of $f_0F2/\overline{f_0F2}$ v. storm-time.

Referring to Fig. 1 it is seen that Dst (f_0F2) at the equatorial station Kodaikanal-Nhatrang shows a small decrease followed by a large and prominent increase of f_0F2 on the second and third day of the storm. At the north and south subtropical stations Kokubunji and Watheroo, Dst (f_0F2) consists of a small initial rise followed by main decrease of f_0F2. Similar behaviour of f_0F2 is seen at equatorial and subtropical stations in the African zone (refer Fig. 2). These results are in conformity with the earlier results.

Referring to Fig. 3 for the stations in the American zone, one finds that the equatorial station Huancayo shows nearly normal behaviour. The f_0F2 at the northern subtropic station, Puerto Rico, shows an initial rise followed by a decrease of f_0F2. However at the southern station Buenos Aires the Dst variation is distinctly different showing increased f_0F2 during the 3 days following the SC storms. This is rather unexpected for a station near the region of daytime f_0F2 maximum.

Referring to Dst (f_0F2) at stations in the Pacific zone (Fig. 4), the northern subtropical station Maui has a negative type of variation but at the southern station Rarotonga, f_0F2 during geomagnetic storms is greater than the normal f_0F2 value for the corresponding hours, somewhat similar to Buenos Aires. It may be noted that the geographic as well as the magnetic latitudes of the two stations Maui and Rarotonga are almost identical except that they are in opposite hemispheres.

Martyn (1953) had shown that the storm time variation of f_0F2 depends upon the local time of the beginning of the storm. The present analysis refers to the same storms at pairs of stations almost along the same longitude and therefore the local times of the storms are identical. The different behaviour of the Dst (f_0F2) at the northern and southern stations cannot be attributed to solar time effect.

Rastogi and Rajaram (1965) have shown that in the December solstitial months during IGY/IGC period the disturbance daily variation of f_0F2 at the equatorial stations in the American zone was quite different from that at Ibadan or at Kodaikanal. These abnormalities seem to be related to the low value of the geomagnetic field and its North–South asymmetry in the American zone. A detailed analysis of the ionospheric storm effects at southern latitude stations is being undertaken to study this abnormal behaviour in relation to the morphology of the geomagnetic field.

Acknowledgement—The authors are pleased to thank Professor K. R. Ramanathan for stimulating discussions during the course of work.

References

Appleton E. V. and L. J. Ingram	1935	*Nature, Lond.* **136**, 548.
Martyn D. F.	1953	*Proc. R. Soc.* **A218**, 1.
Matsushita S.	1959	*J. Geophy. Res.* **64**, 305.
Rastogi R. G.	1961	*Proc. Indian Acad. Sci.* **54A**, 155.
Rastogi R. G.	1966	*J. Instn Telecommun. Engrs.* **12**, 245.
Berkner L. V. and S. L. Seaton	1940	*Terr. Magn. Atmos. Elect.* **45**, 419.
Skinner N. J. and R. W. Wright	1955	*J. Atmosph. Terr. Phys.* **6**, 177.
Rastogi R. G. and Rajaram G.	1965	*J. Atmosph. Terr. Phys.* **27**, 1097.

Paper 2

Journal of Atmospheric and Terrestrial Physics, 1970, Vol. 32, pp. 113–118. Pergamon Press. Printed in Northern Ireland

SHORT PAPER

North–South asymmetry of ionospheric storms—dependence on longitude and season

GIRIJA RAJARAM and R. G. RASTOGI
Physical Research Laboratory, Ahmedabad-9, India

(*Received* 20 *May* 1969)

Abstract—The study of ionospheric storms at pairs of north and south mid-latitude stations in different longitude zones, individually for each season, has shown asymmetry in their behaviour, most significantly in the Pacific zone, to some extent in the Asian and American zones. The decrease of f_0F2 which is found to occur during geomagnetic storms in Summer months is conspicuously absent at Rarotonga. This suggests that ionospheric storm variations are greatly affected by horizontal and vertical movements of ionisation, which are controlled by the asymmetric magnetic field of the Earth.

THE EARLIEST ionospheric observations showed that *F2*-layer critical frequencies (f_0F2) were greatly affected by magnetic disturbances (APPLETON and INGRAM, 1935; BERKNER and SEATON, 1940). Following the method of analysis used by Moos and Chapman for studying magnetic storms, MARTYN (1953) studied both the disturbance diurnal (SD) and storm-time (D_{st}) variations of ionospheric parameters at a few stations. MATSUSHITA (1959) studied D_{st} variations at a large number of stations, and suggested that the D_{st} variation is similar at stations having comparable dipole latitudes N or S. The ratio of storm-time f_0F2 at any hour to the median f_0F2 for the same hour ($f_0F2/\overline{f_0F2}$), for low-latitude stations is greater than unity for any of the seasons, i.e. the storms increase the value of f_0F2 and are called positive storms. At high latitudes the ratio is less than unity for any of the seasons, i.e. the storms decrease the value of f_0F2 and are called negative type. At mid-latitudes, the effect is more of equatorial type in Winter, and of high latitude type in Summer. RASTOGI (1962) showed that the character of $D_{st}(f_0F2)$ variation is controlled by the dip, and not by the dipole latitude of the station.

RAJARAM and RASTOGI (1968) found significant asymmetry in $D_{st}(f_0F2)$ variations at pairs of ionospheric stations of comparable dip angle for certain longitude zones. The results were based on the annual average D_{st} variations for the low sunspot period, 1951–1956. The present work describes $D_{st}(f_0F2)$ variations at pairs of stations in the N and S in different longitude zones for each of the seasons of the high sunspot period, 1957–61. Only strong magnetic storms of this period in which $A_p \geq 50$ on any of the 3 succeeding days were used. A total of about 100 storms have been studied for each station, which means an average of about 30 storms for each

season, the storms being the same, as far as availability of data allowed. The geographic coordinates and the magnetic dip of the stations studied in this article are given in Table 1.

Table 1. Geographic coordinates and the magnetic dips of stations studied

Station	Geographic Lat.	Geographic Long.	Dip angle
Akita	39°N	140°E	53°N
Brisbane	27°S	152°E	57°N
Puerto Rico	18°N	67°W	51°N
Port Stanley	51°S	57°W	48°S
Buenos Aires	34°S	58°W	31°S
Maui	20°N	156°W	40°N
Rarotonga	21°S	159°W	40°S

Figure 1 shows D_{st} variations for pairs of stations in the Asian zone, namely Akita (Dip 53°N) and Brisbane (Dip 57°S). The annual average D_{st} variations at either of the stations is of negative type, the change being larger at Brisbane than at Akita. During local Summer and equinoxes, the variations are almost identical at both the places, and definitely of the negative type. During local Winter months, D_{st} is definitely positive at Akita, and rather uncertain at Brisbane indicating if at all some positivity; there are significantly large 24-hr oscillations in the D_{st} variation at Brisbane.

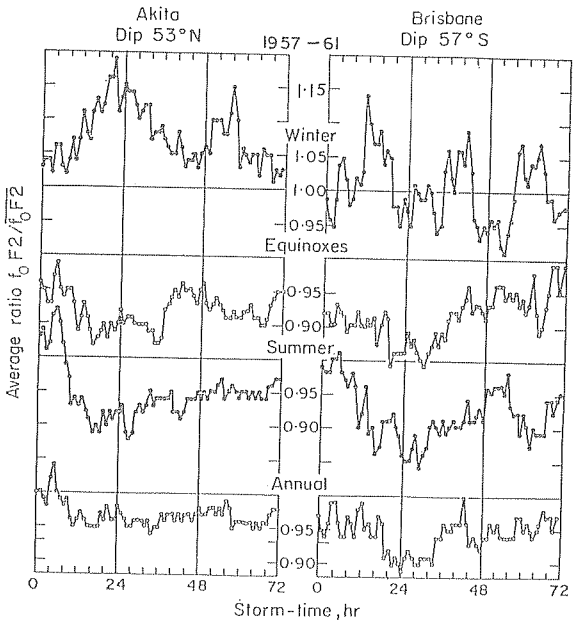


Fig. 1. Storm-time variation of f_0F2 for each season at N and S sub-tropical stations of Asian zone.

Figure 2 shows D_{st} variations at three stations in the American zone, namely, Puerto Rico (Dip 51°N), Port Stanley (Dip 48°S) and Buenos Aires (Dip 31°S). The annual D_{st} variation at Puerto Rico shows a very small positive at the beginning of the storm, followed by mainly negative phase. The annual D_{st} variation at Port

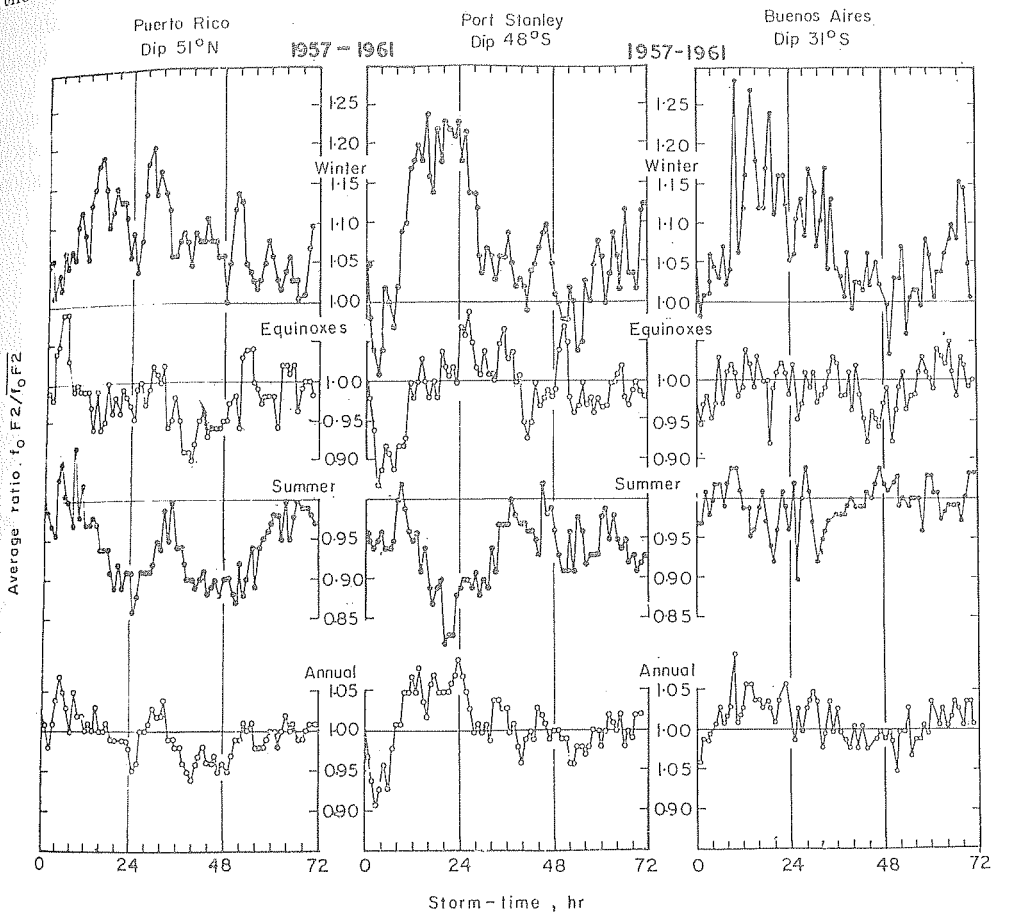


Fig. 2. Storm-time variation of f_0F2 for each season at N and S sub-tropical stations of American zone.

Stanley shows a small negative, followed by a positive, ending with a slight negative phase. The annual average D_{st} variation at Buenos Aires is positive on the first day of the storm, and slightly negative on the second day, somewhat similar to that at Port Stanley. During local Summer, the D_{st} variation at all the three stations is of similar nature, the change being significantly smaller at Buenos Aires, than at the other two stations. During equinoxes, the variation at Puerto Rico is negative, while at Port Stanley, it is positive around 24 hr storm-time, the changes at Buenos Aires being small and uncertain. During local Winter, D_{st} is positive at any of the three stations, although the effects are stronger at Port Stanley and Buenos Aires than at Puerto Rico.

It is to be noted that D_{st} variation during the equinoxes at either the N or S station in the Asian zone is strongly negative in character, almost of the same magnitude as in the Summer months. Consequently, the annual average D_{st} variation in the Asian zone is negative. In the American zone, D_{st} in the equinoxes is negative at Puerto Rico, slightly positive at Port Stanley, and almost negligible at Buenos Aires. This makes the annual average D_{st} variation different in the north and south stations in this zone.

Figure 3 shows $D_{st}(f_0F2)$ variations at pairs of stations in the Pacific zone, namely Maui (Dip 40°N) and Rarotonga (Dip 40°S). The annual average $D_{st}(f_0F2)$ variation is generally negative at Maui, and positive at Rarotonga. At Maui, the D_{st} variation

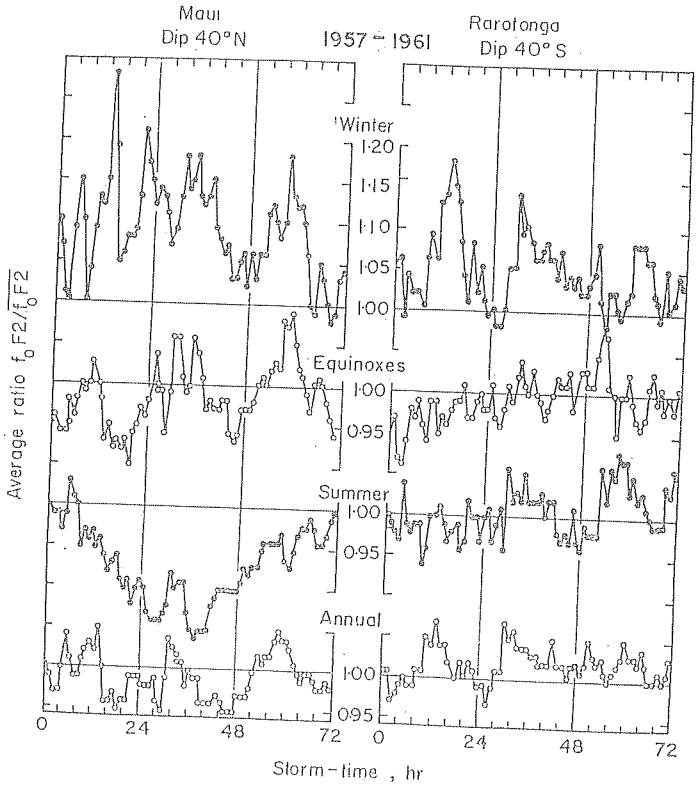


Fig. 3. Storm-time variation of f_0F2 for each season at N and S sub-tropical stations of Pacific zone.

is distinctly negative during local Summer and positive during local Winter. At Rarotonga, D_{st} is distinctly positive during local Winter, but tends to be positive even during local Summer. During equinoxes, D_{st} variation at Rarotonga is small, being slightly negative on the first, and slightly positive on the second day of the storm, while at Maui, variations have a large 24-hr component over a smooth variation which would be similar to that at Rarotonga. Thus during local Summer months, the D_{st} variations at the two stations are completely dissimilar. It is to be noted that this pair of stations is a conjugate pair, and is located on the same longitude zone.

Instead of comparing D_{st} variations for N and S stations for the same local season, one can compare the variations during the same groups of months. This has the advantage that the same magnetic disturbances are involved for the two stations. In Fig. 4 are shown D_{st} variations for the same month-groups at pairs of N–S stations in all the three zones; full lines represent the northern stations, and the dotted lines the southern stations. Since during the same months, the local seasons are opposite at the N and S stations, the D_{st} variations at the two stations should be opposite in nature, if N–S asymmetry is absent.

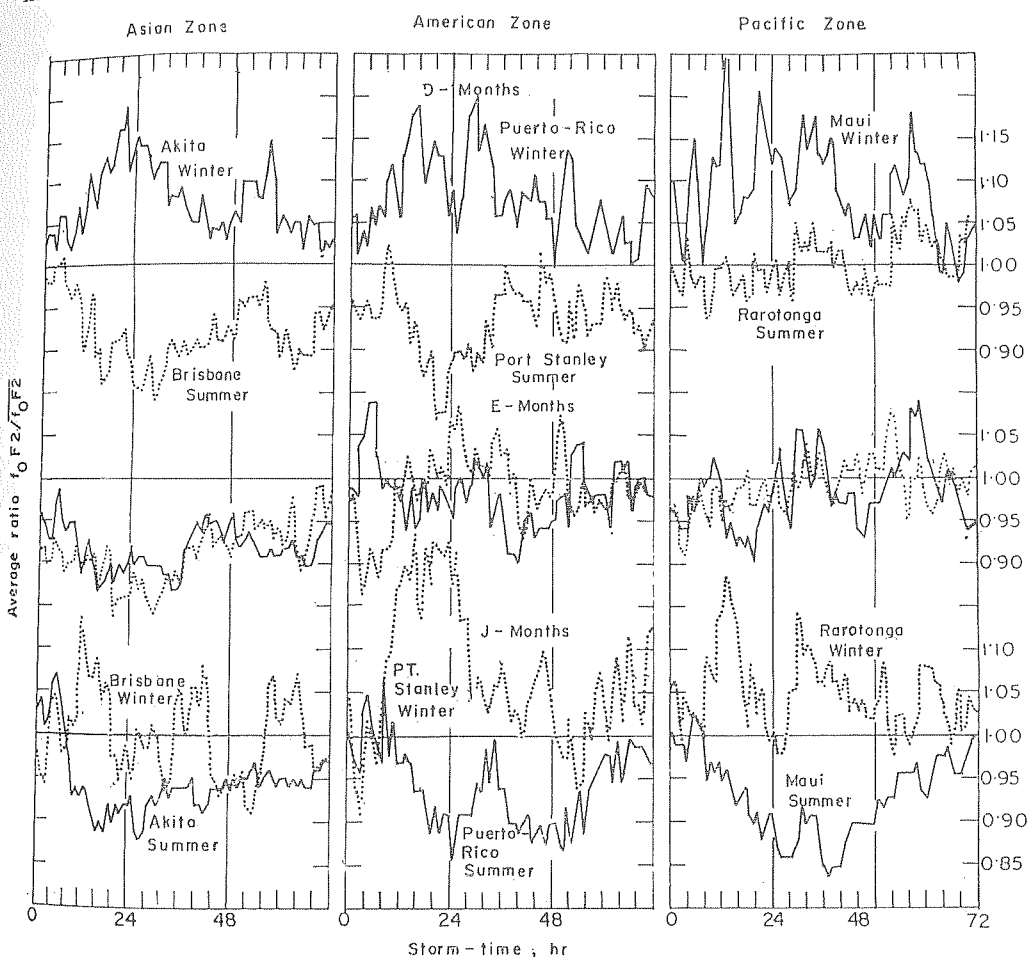


Fig. 4. Storm-time variation of f_0F2 for Asian, American and Pacific zones comparing N–S behaviour for identical storms.

Referring to the variations during the D-months at N–S stations, one finds that the curves are opposite in character in the Asian and American zones and not so in the Pacific zone. Examining the smaller fluctuations, one notices that up to about 36 hr these are opposite in character at the Asian and American zones. The smaller fluctuations are almost in phase at the two stations during 36–72 hr in Asian and American zones, and during the entire 0–72 hr in the Pacific zone.

During the equinoxes, one finds that the variations are almost similar for the two stations both for the general behaviour as well as for the shorter fluctuations. For the American zone the variations seem to be opposite in character for the first 6 hr. The magnitude of D_{st} variations is very small at American and Pacific stations, and large (negative type) at Asian stations.

During the J-months the variations are in general opposite in nature at the two stations in the American and Pacific zones, while in the Asian zone, there is no distinct relationship between the two.

It is suggested that the effect of magnetic storms at middle and high latitudes is controlled by both horizontal and vertical movements and other dynamical processes in the F-region which are not symmetric in the N and S hemispheres due to the asymmetry of the Earth's magnetic field and which seem to depend a good deal on the season. Further studies of this asymmetry are being continued.

Acknowledgements—The authors are grateful to Professor K. R. Ramanathan for stimulating discussions and the authorities of the respective observatories and WDC 'A' at Boulder, for the data used in this study.

References

Appleton E. V. and Ingram L. J. 1935 *Nature, Lond.* **136,** 548.
Berkner L. V. and Seaton S. L. 1940 *Terr. Magn. atmos. Elect.* **45,** 419.
Martyn D. F. 1953 *Proc. R. Soc.* **A218,** 1.
Matsushita S. 1959 *J. geophys. Res.* **64,** 305.
Girija Rajaram and Rastogi R. G. 1968 *J. Atmosph. Terr. Phys.* **30,** 651.

4.4 Explanation of North-South asymmetry in $D_{st}(f_oF_2)$

This asymmetry in storm-time f_oF_2 variation could be due to the uneven configuration of the earth's geomagnetic field described in detail in Chapter 1.

Surface anomalies are irregularities in the field caused by uneven deposits of ferromagnetic materials in the thin crust of the earth. These exist only in localised areas (Handbook of Geophysics 1961). One such anomalous area is the South American zone, with its very low field intensity of only 0.25 gauss at the centre. In fact there is a girdle of low field intensity over a large area extending from the South Pacific, through South America to South Africa.

This low field intensity will have considerable effect on the mirror points of charged particles drifting in the inner radiation belt. As described in Section 1.9, the mirror altitudes of the particles are considerably lowered as they drift towards the longitude of this low-field anomaly region. Those whose mirror altitudes come down low enough are lost in the atmosphere (Cladis and Dessler 1961; Williams and Kohl 1965; Imhof and Smith 1965; Paulikas and Freden 1964; Gledhill and Van Rooyen 1962; Sharp et al., 1966). It may be the secondary ionisation caused by these particles which is observed as the enhanced storm-time F_2 ionisation in the South Pacific and South American temperat- latitudes.

Satellite studies have shown the enhanced concentration of ionisation over such anomalous zones. Knudsen and Sharp (1968) found a region of enhanced electron concentration at F_2 peak heights from a study of flux distribution of 10 eV electrons measured from the satellite 1962 A1. They carried out another flight in 1963 and found that besides an anomalous F_2 region in the south Pacific, there is a second region of enhanced concentration extending approximately from the South Atlantic magnetic anomaly to the eastern edge of Africa. These results support the observations of storm-time f_oF_2 made here in the S.Pacific and S.American zones.

4.5 D_{st} (f_oF_2) dependence on time of storm commencement

Some workers believe that the shape of the D_{st} (f_oF_2) curve depends on the local time at which a storm starts. Harang (1937) from studies at Tromso, a high-latitude station, found that the major depression of f_oF_2 was seen the day after the magnetically disturbed day. Appleton and Piggott (1952) showed that the form of the N_mF_2 variations depends on the local time of start of the storm. L.Thomas and Venables (1966) found that the major changes in N_mF_2 in mid-latitudes depend on the local time at which the main phase of the magnetic storm begins. If it occurred at night, there was an immediate depression of N_mF_2, but not if it occurred by day. Kotadia and Ramanathan (1961) from a study of disturbances at Ahmedabad

found that the changes in f_oF_2 are chiefly governed by the local time of sudden commencement of a magnetic storm.

Here a detailed study of the dependence of the D_{st} (f_oF_2) variation on the local time of commencement of the storm is made for the IGY-IGC period for the same stations chosen for seasonal studies. Again the storms are all strong ones, with Ap $\geq$ 50 on any of the 3 days following the storm. They are broadly classified into two categories - one with commencement in the daytime (between 06 hr. and 18 hr.) and the other with commencement in the night-time (between 18 hr. and 06 hr.). A further classification into storms with commencement in the pre-noon (06-12) hr. post-noon (12-18) hr., pre-midnight(18-24)hr, and post-midnight (00-06) hr, periods was tried but the number of storms in each of the four categories was insufficient and statistically-significant results could not be obtained.

(1) Equatorial stations (fig. 4.5) (Pg. 90 (a))

For storms which have their commencement in the daytime, after a slight drop of f_oF_2 , there is a clear positive type of D_{st} (f_oF_2) variation. This is so at both Huancayo (West zone) and Trivandrum (East zone). Storms with night-time commencement show larger fluctuations of ratio such that sometimes the ratio is less than 1.00.

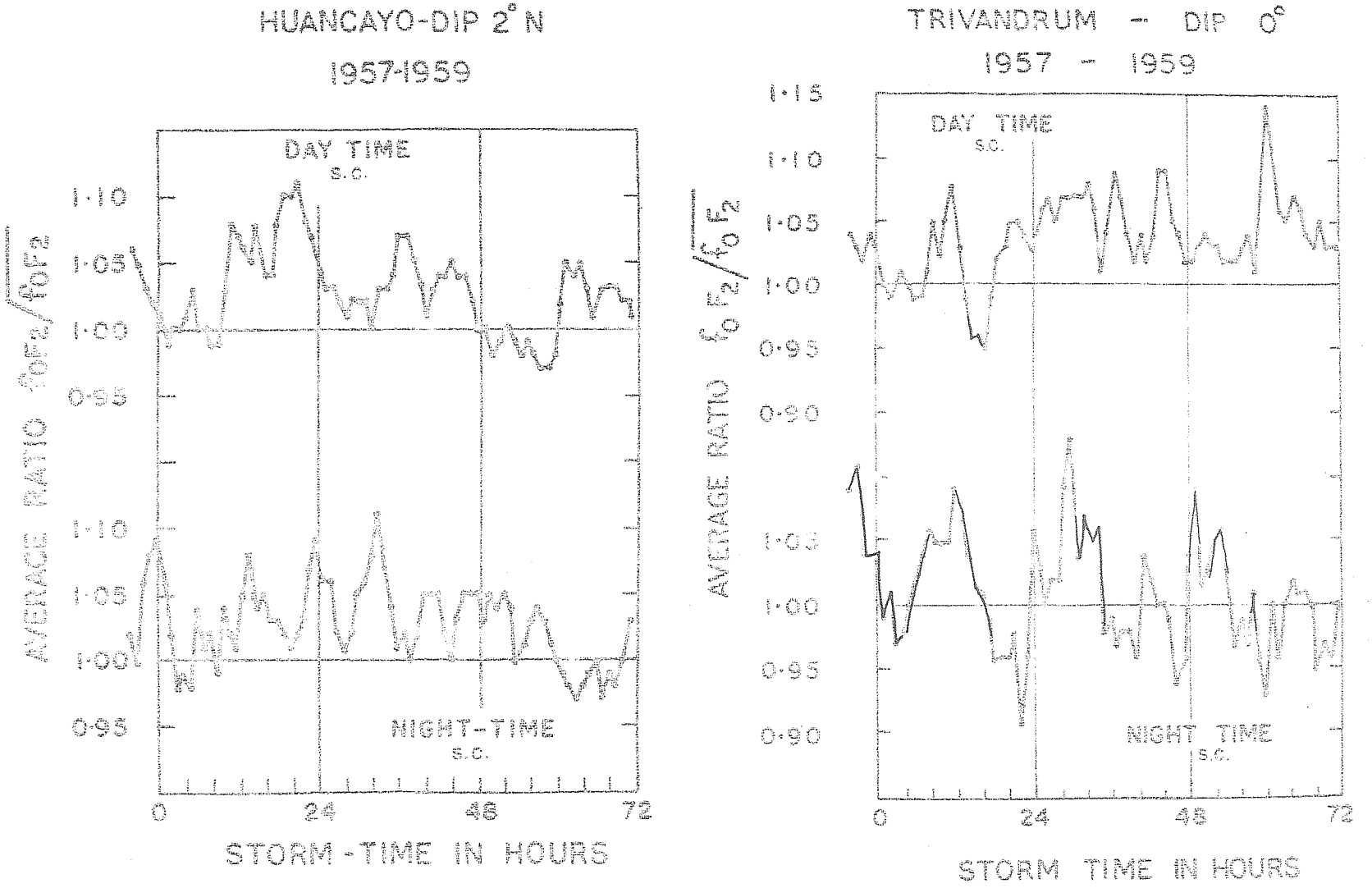

HUANCAYO-DIP 2° N
1957-1959
DAY TIME
S.C.
NIGHT-TIME
S.C.
AVERAGE RATIO foE2/foF2
1·10
1·05
1·00
0·95
0
24
48
72
STORM-TIME IN HOURS
TRIVANDRUM - DIP 0°
1957 - 1959
DAY TIME
S.C.
NIGHT TIME
S.C.
AVERAGE RATIO foE2/foF2
1·15
1·10
1·05
1·00
0·95
0·90
STORM TIME IN HOURS

FIG 4·5

(2) Low-latitude stations (Fig. 4.6)(Pg. 91(a))

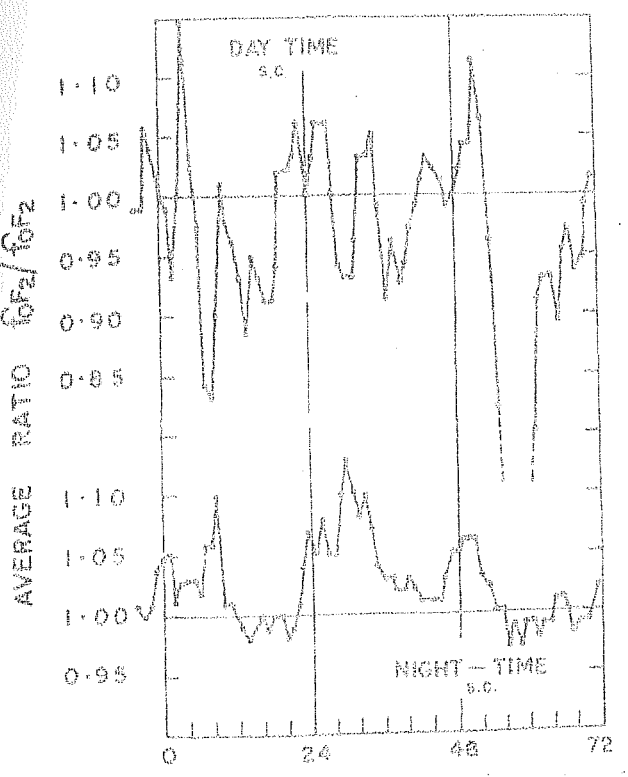
Daytime commencement storms show an uncertain variation at Talara (13°N dip), but the night-time ones show a clear positive variation. At Baguio, both night-time and daytime commencement show a positive variation. At Tucuman, (22°S dip) there seems to be an anti-correlation between the D_{st} ($f_{o}F_{2}$) variations with daytime commencement and night-time commencement. At Singapore, both daytime and night-time commencement storms start with a drop, and a positive phase is shown mainly on the second day of the storm. Not much north-south asymmetry is seen when northern and southern stations in the same zone are compared.

(3) Mid-latitude stations (fig. 4.7) (Pg. 91 (b))

We now study the variations at mid-latitude stations Puerto Rico (dip 51°N) and Port Stanley (dip 46°S) in the West zone, and Akita (dip 53°N) and Townsville (dip 48°S) in the East zone. The striking point about all these stations is that storms with daytime commencement and night-time commencement have clear anti-correlation. Daytime commencement storms begin with a rise in $f_{o}F_{2}$ on the first day, a drop in $f_{o}F_{2}$ from 20 hr to 36 hr and then a rise. Night-time commencement storms begin with a clear drop in($f_{o}F_{2}$), a rise around 24 hr. to 36 hr. and then a drop.

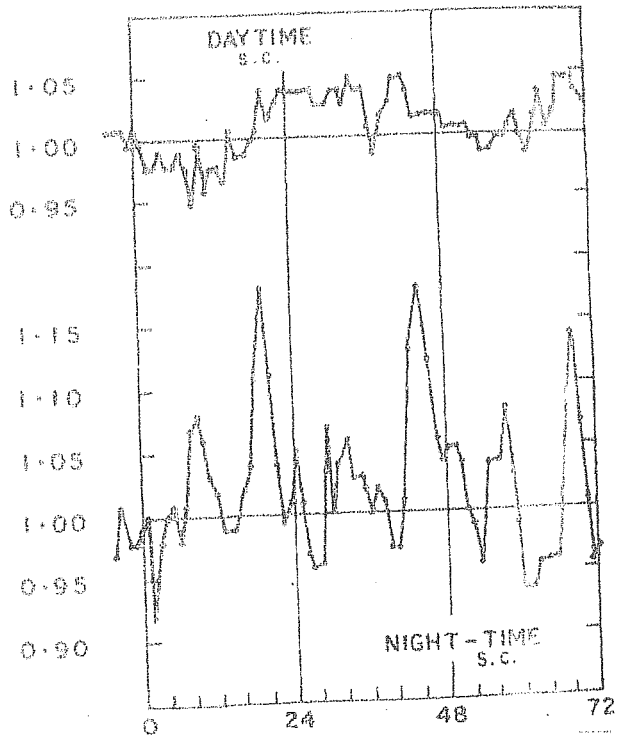
TALARA — DIP 13° N

1957 — 1959



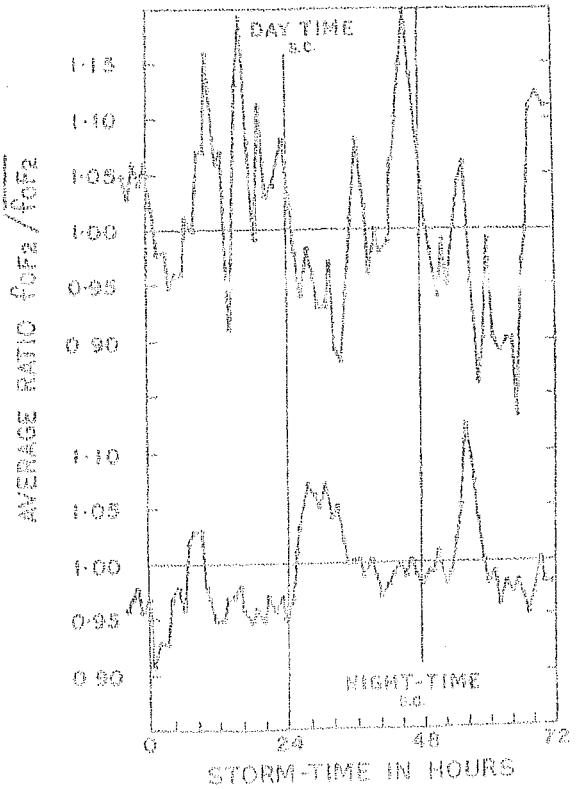
BAGUIO — DIP 19° N

1957 — 1959



TUCUMAN - DIP 22° S

1957 - 1959



SINGAPORE - DIP 18° S

1957-1959

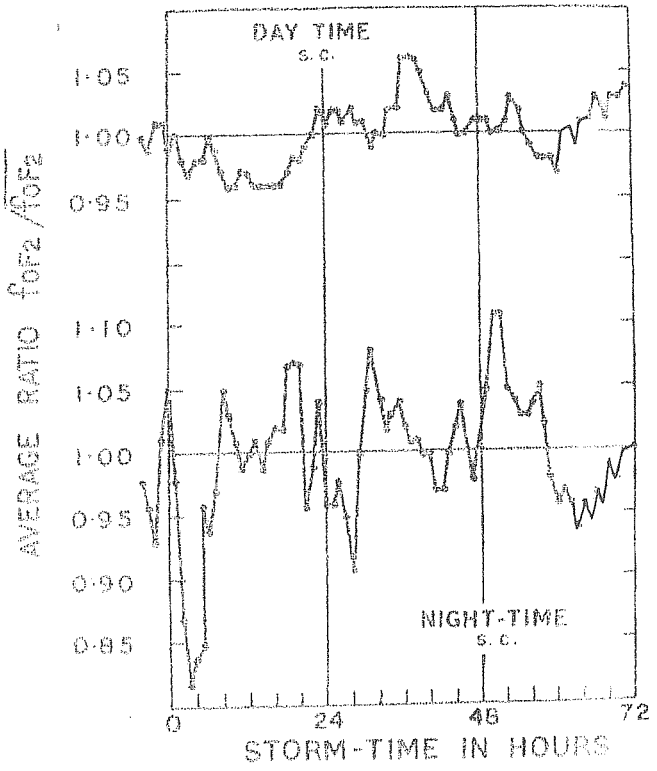
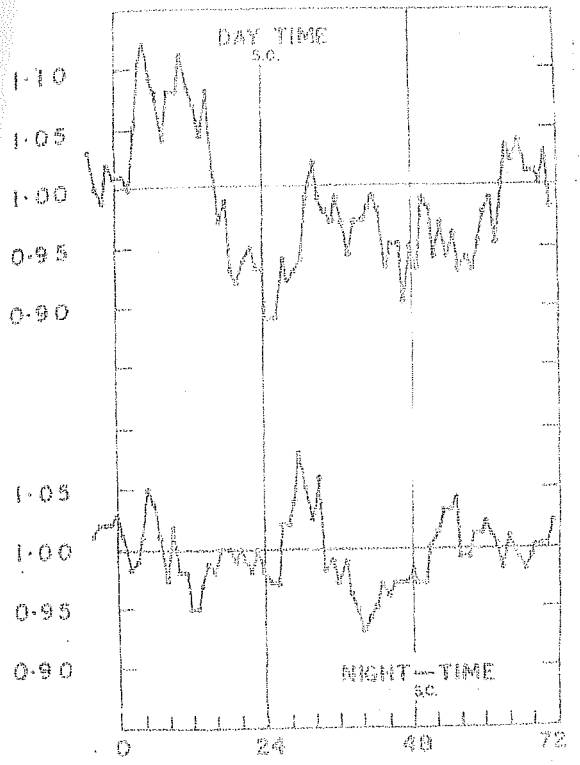


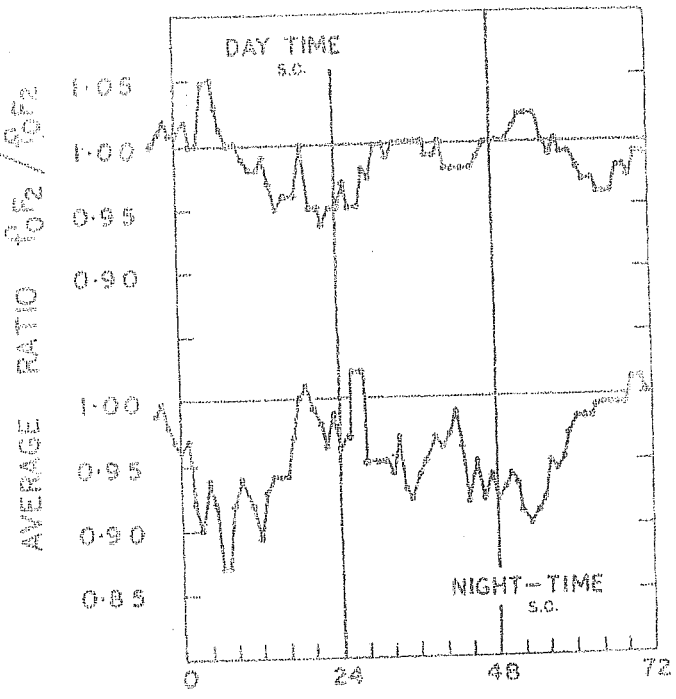
FIG - 4.6

PUERTO RICO – DIP 51° N
1957 – 1959

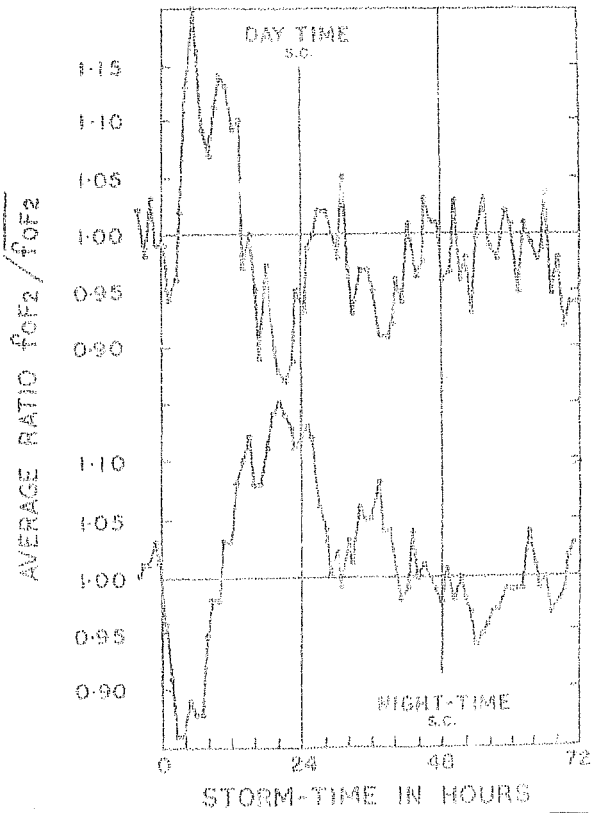


PORT STANLEY DIP 46° S
1957-1959

AKITA – DIP 53° N
1957 – 1959



TOWNSVILLE – DIP 48° S
1957 – 1959



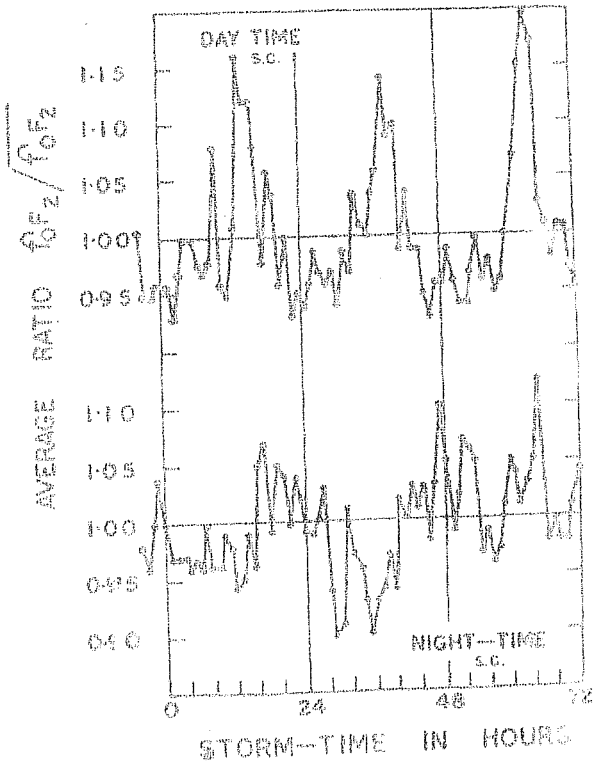


Fig 4·7

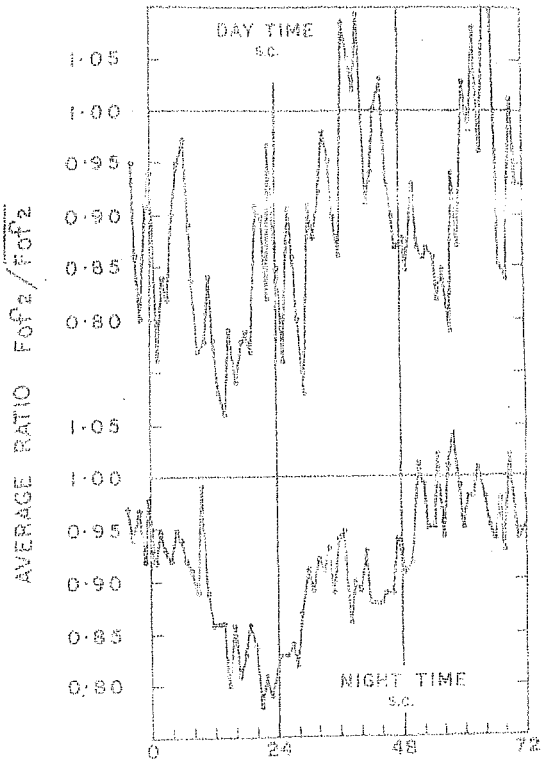
The opposite tendency is very clear and there is even some correlation between the peaks of one with the troughs of the other. Some north-south asymmetry is seen between northern and southern stations in the same zone, but this is more in the magnitude than in the shape of the variation.

(4) High-latitude stations (Fig. 4.8) (Pg. 92 (a))

Both daytime commencement storms and night-time commencement storms show large and rapid ratio-fluctuations at high-latitudes. In the northern hemisphere at both Resolute Bay (dip 89°N) and Tixie Bay (dip 83°N), the ratio $f_oF_2 / \overline{f_oF_2}$ is well below 1.00 even at the zero-hour of the storm. This aspect is rather puzzling as after a depression of f_oF_2 around 24 hours (this is the time when the peak effect on f_oF_2 occurs) the f_oF_2 values return to normal in the following 48 hours. In the southern hemisphere, the characteristic feature of depressed f_oF_2 at zero hour is not seen at either South Pole (dip 75°S) or Scott Base (dip 83°S) for either the daytime commencement or night-time commencement storms. Again the peak effect of disturbances on f_oF_2 occurs around 24 hours, and then normal values are reached in the next 48 hours. The variations are chiefly negative. Little North-south asymmetry is seen.

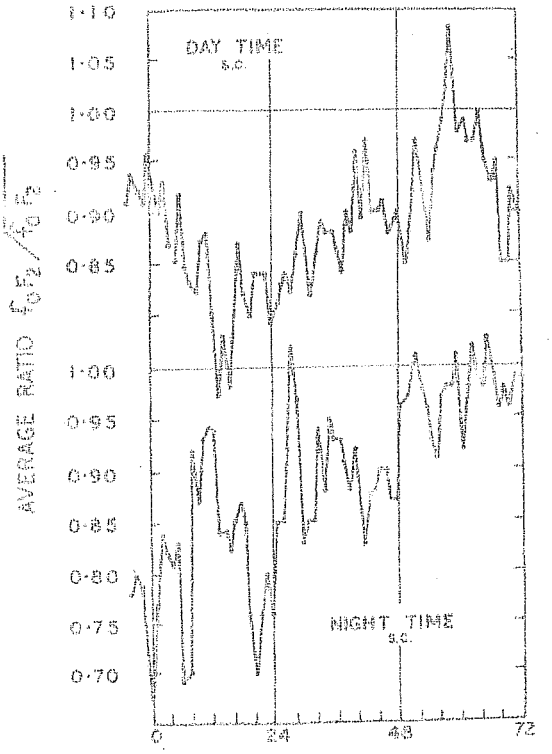
RESOLUTE BAY DIP-89°N

1957-1959



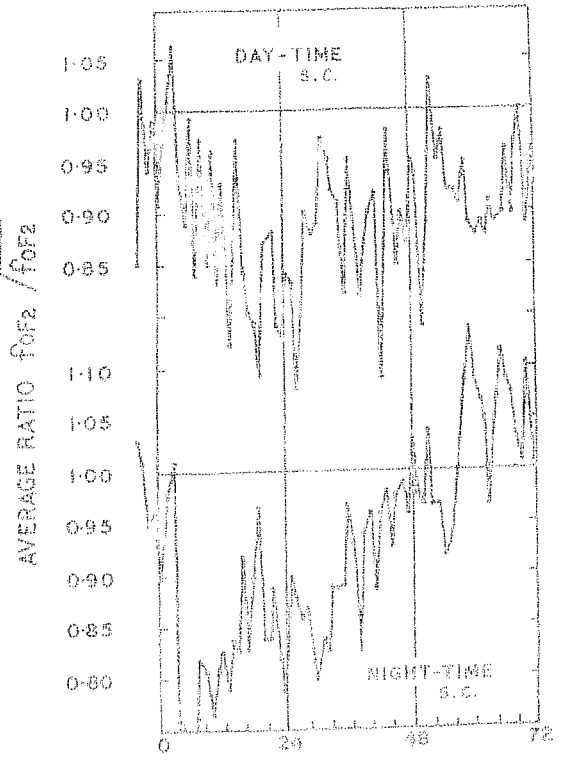
TIXIE BAY - DIP 83° N

1957 - 1959



SOUTH POLE-DIP 75° S

1957-1959



SCOTTBASE - DIP 83° S

1957 - 1959

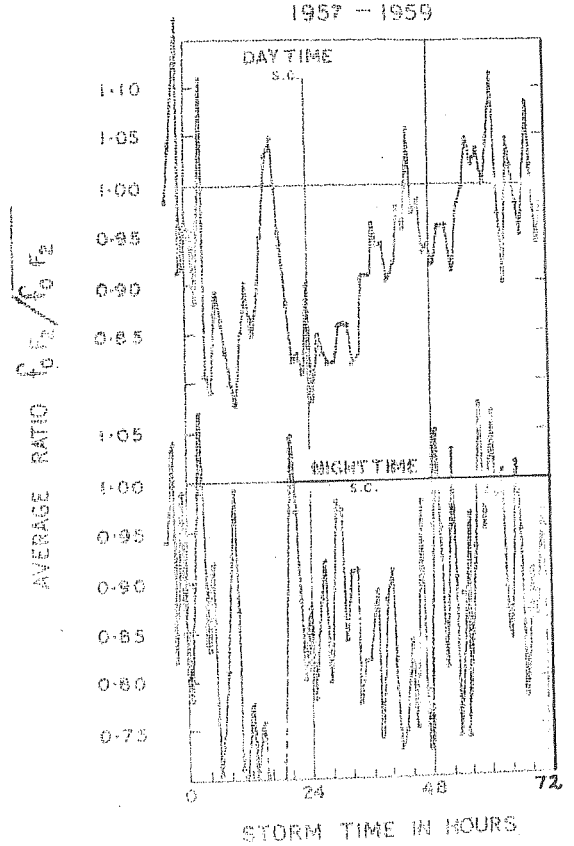


FIG 4-8

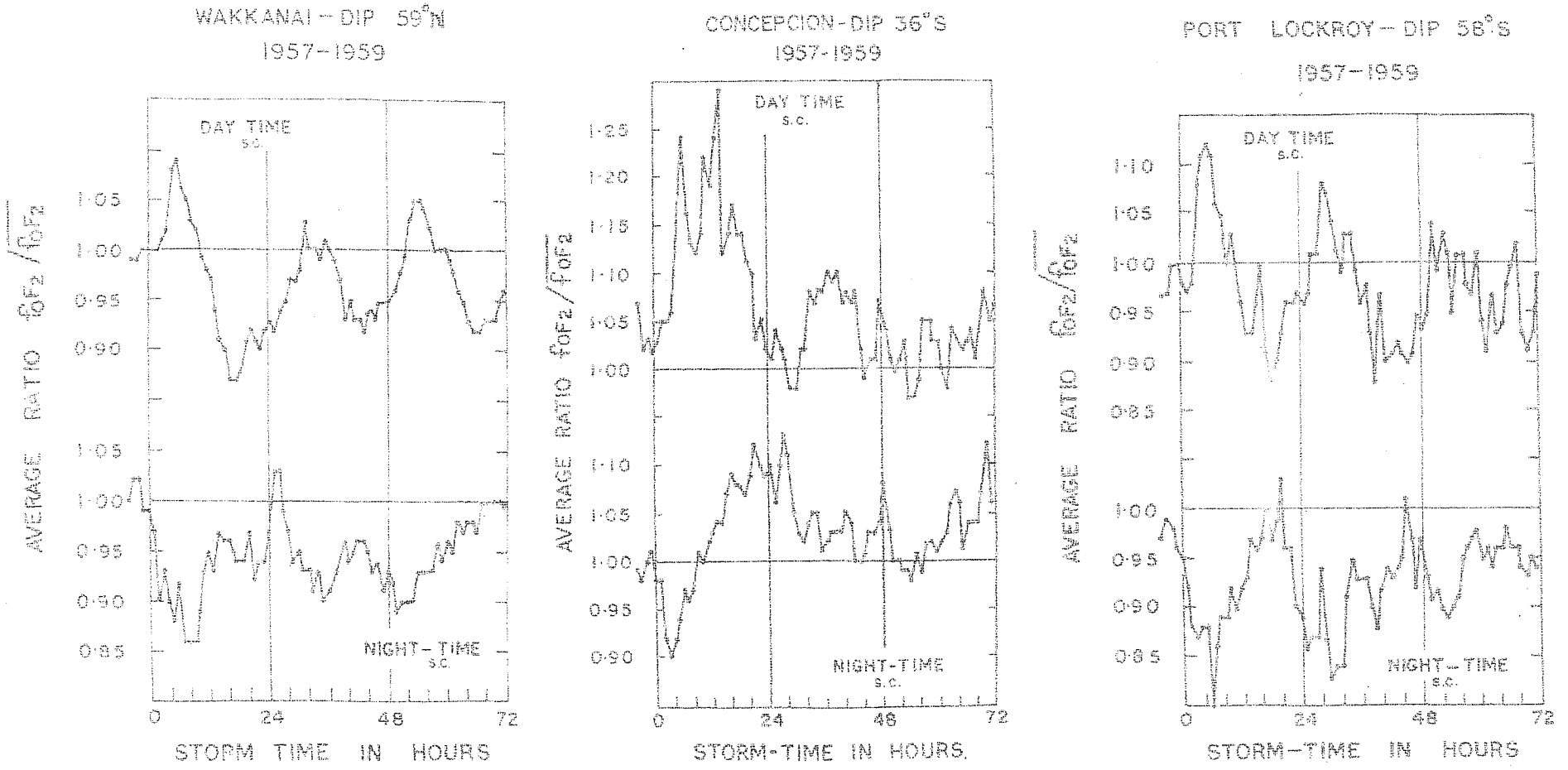

WAKKANAI – DIP 59°N
1957–1959
DAY TIME
S.C.
NIGHT–TIME
S.C.
AVERAGE RATIO foF2 / foF2
1·05
1·00
0·95
0·90
0·85
0
24
48
72
STORM TIME IN HOURS
CONCEPCION–DIP 35°S
1957–1959
DAY TIME
S.C.
NIGHT–TIME
S.C.
AVERAGE RATIO foF2 / foF2
1·25
1·20
1·15
1·10
1·05
1·00
0·95
0·90
0
24
48
72
STORM–TIME IN HOURS.
PORT LOCKROY – DIP 58°S
1957–1959
DAY TIME
S.C.
NIGHT–TIME
S.C.
AVERAGE RATIO foF2 / foF2
1·10
1·05
1·00
0·95
0·90
0·85
0
24
48
72
STORM–TIME IN HOURS

Fig 4·9

92(5)

Conclusions

From this study, one comes to the conclusion that the behaviour of D_{st} (f_oF_2) for daytime commencement storms and night-time commencement storms is not remarkably different at equatorial, low-latitude, and high-latitude stations. At mid-latitude stations, they are vastly different, the D_{st} (f_oF_2) variation for daytime commencement storms being exactly opposite to variation of night-time commencement storms. This is borne out by the f_oF_2 variations of daytime and night time commencement storms at three other mid-latitude stations - Wakkanai (dip 59°N), Concepcion (dip 36°S) and Port Lockroy (58°S dip) as shown in Fig.4.9 (Pg. 92(b)).

4.6 (f_oF_2 variations on magnetically Quiet and Disturbed days S_q (f_oF_2) and S_d (f_oF_2).

Detailed studies of D_{st} (f_oF_2), and S_q (f_oF_2) and S_d (f_oF_2), are given in the Papers (3,4,5) following this page. Such variations are for individual stations in the Asian zone (Rajaram and Rastogi 1969), Australian zone (Rajaram and Rastogi 1970) and the American zone (Rajaram and Rastogi 1971) for the high sunspot period of IGY-IGC.

(Papers 3,4,5 follow overleaf)

Ann. Géophys., t. 25, fasc. 4, 1969, p. 795 à 805.

Paper 3

A synoptic study of the disturbed ionosphere during IGY-IGC-(1) the Asian Zone

by GIRIJA RAJARAM and R. G. RASTOGI,

Physical Research Laboratory,
Ahmedabad-9, India.

RÉSUMÉ. — *On a conduit une étude systématique de variation solaire journalière S_D (f_0F_2) et de la variation avec le temps de l'orage D_{st} (f_0F_2) pour les stations de la zone asiatique et pour chacune des saisons de la période IGY-IGC. Le passage du type équatorial au type polaire de tempête ionosphérique se fait à une latitude qui varie de façon appréciable avec la saison. Il en résulte que l'étude des orages ionosphériques sur une base annuelle peut conduire à des conclusions erronées.*

Pendant les mois d'hiver local, toutes les stations de la zone asiatique à l'exception de celles comprises entre 10 et 20° de latitude d'inclinaison et au-dessus de 60° de latitude d'inclinaison, ont des perturbations ionosphériques de type positif. On suggère que les effets d'orage ionosphérique aux stations qui sont situées dans la bande 0° — 20° d'inclinaison, sont produits par la modification du développement diurne de l'anomalie équatoriale engendrée par la perturbation géomagnétique. Les latitudes moyennes sont affectées par l'effet combiné des perturbations qu'elles produisent à l'équateur aussi bien que dans les hautes latitudes, particulièrement pendant l'hiver local.

ABSTRACT. — *A systematic study of the solar daily variation $S_D(f_0F_2)$ and the storm-time disturbance variation $D_{st}(f_0F_2)$ has been made for stations in the Asian zone for each of the seasons of the IGY-IGC period. The latitude of change-over of the equatorial to the high-latitude type of ionospheric storm, varies appreciably with season. This may cause the consideration of ionospheric storms on an annual basis to lead to erroneous conclusions. During local winter months, all the stations in the Asian zone, except those between 10° and 20° dip latitude, and above 60° dip latitude, have positive type of ionospheric disturbances. It is suggested that the ionospheric storm effects at stations within 0° — 20° dip, are due to the modification of the diurnal development of the equatorial anomaly, caused by the geomagnetic disturbance. The mid-latitudes are affected by the combined effect of disturbances arising at the equator as well as at the high latitudes, especially during the local winter months.*

INTRODUCTION

Since the epic work of APPLETON and INGRAM [1935] n the effect of magnetic storms on the ionosphere, udies have been made by many workers, to name few, BERKNER and SEATON [1940], MARTYN [1953], AYASHI [1954], NAGATA [1954], SKINNER and RIGHT [1955], SATO [1956], MAEDA [1959], MAT-SHITA [1959] and THOMAS and VENABLES [1966]. The higher latitudes have been studied by IGNATOV [1962], KIYANOVASKIY and MEDNIKOVA [1963], DOLGOVA [1965], FELDSHEYN [1965] and others. BHARGAVA [1959] and KOTADIA [1961] have made a study of the Indian stations.

The understanding on the basis of all this work is, that a magnetic disturbance generally increases f_0F_2 at equatorial latitudes, and decreases f_0F_2 at high latitudes. Mid-latitudes seem to show a seasonal

change-over, exhiting equatorial behaviour in local winter, and high latitude behaviour in local summer.

The daily variation of f_0F_2 at a station has been shown to depend on the ionisation locally produced, as well as on that transported from the equator, along the lines of the earth's magnetic field [RASTOGI, 1959, 1960]. The daily variation of f_0F_2 thus greatly depends on the spatial distribution of the magnetic field in the region concerned. The Asian zone, for this reason, simple to study, as the isodip lines are parallel to the lines of geographic latitude. synoptic study of the variation of the F_2 region the Asian zone has already been described by R TOGI [1960], and it was therefore decided to st the ionospheric storm behaviour for the same zo within the longitudes 75 °E and 150 °E.

TABLE I

Stations studied in the Asian zone with their geographic and magnetic coordinates.

Station	Abreviation used	Geographic		Magnetic	
		Latitude	Longitude	Dip	Latitude
Trivandrum	TVD	8°25′ N	77° 0′ E	0°	0°
Kodaikanal.....	KOD	10°14′ N	77°29′ E	+ 3.5°	2°
Tiruchi	TIR	10°50′ N	78°50′ E	+ 5.0°	2°
Madras.....	MAD	13°00′ N	80°15′ E	+ 10.0°	5°
Baguio	BAG	16°25′ N	120°35′ E	+ 19.0°	10°
Ahmedabad.	AHM	23°01′ N	72°36′ E	+ 33.0°	18°
Okinawa.....	OKI	26°19′ N	127°47′ E	+ 36.0°	20°
Delhi.....	DEL	28°35′ N	77°13′ E	+ 42.0°	24°
Yamagawa.....	YAM	31°13′ N	130°38′ E	+ 43.0°	25°
Kokubunji	KOK	35°42′ N	139°29′ E	+ 49.0°	30°
Akita	AKT	39°44′ N	148°08′ E	+ 53.0°	33°
Wakkanai	WAK	45°24′ N	141°41′ E	+ 59.0°	40°
Alma Ata.....	ALM	43°12′ N	76°55′ E	+ 62.0°	43°
Irkutsk	IRK	52°28′ N	104°02′ E	+ 72.0°	57°
Tomsk.....	TOM	56°28′ N	84°58′ E	+ 74.0°	61°
Yakutsk	YAK	62°01′ N	129°43′ E	+ 76.0°	63°
Salekhard.....	SKD	66°35′ N	66°40′ E	+ 79.0°	69°
Tixie Bay	TIX	71°34′ N	128°54′ E	+ 83.0°	76°

The stations chosen for the analysis are given in Table 1 with their respective geographic and magnetic coordinates, and their alphabetical abbreviations, which have been used throughout the paper. The positions of these stations are shown in Figure 1, on which lines of same dip latitude are also drawn. It is seen that the combination of Indian, Japanese and Russian stations, forms a systematic and close distribution of stations from the magnetic equator to about 80° dip.

The annual average noon value of f_0F_2 at these stations has been plotted against the dip angle of the stations in Figure 2, showing the well-known equatorial anomaly. The high-latitude spur discussed by THOMAS [1964] is also evident around 70° dip. The maximum f_0F_2 is seen to occur at Ahmedabad. The stations, TVD, KOD, TIR and MAD are within the equatorial trough, while all t Japanese stations are beyond the tropical pe The Russian stations are very close to the sp region, while Tixie Bay seems to be almost outsi the spur, and is in the Arctic region. The effect the magnetic disturbance would naturally depe on the position of the station on the curve in Figure

Disturbance solar daily variation $S_D(f_0F_2)$.

The disturbance solar daily variation for all the stations, during each season, has been studied comparing the solar daily variation of f_0F_2 averag on 5 International Quiet days (Q) and 5 Internatio Disturbed days (D) of each month, as published the IAGA bulletins.

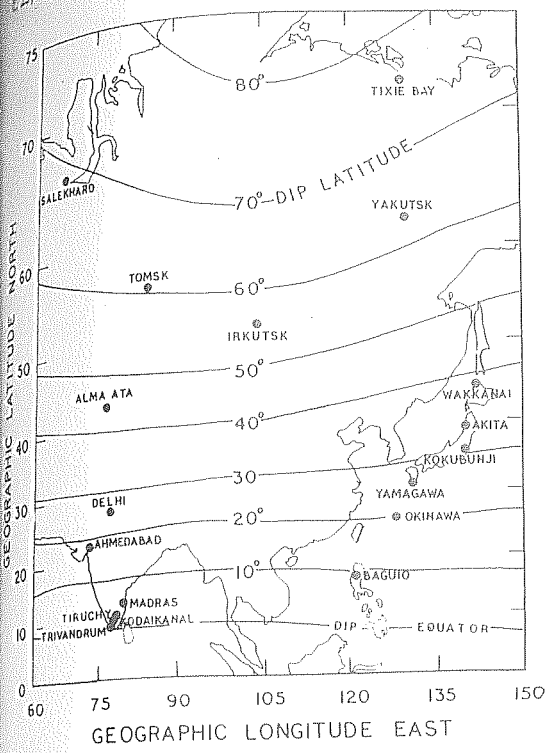


FIG. 1

Map showing the geographic and magnetic locations of stations studied in Asian zone.

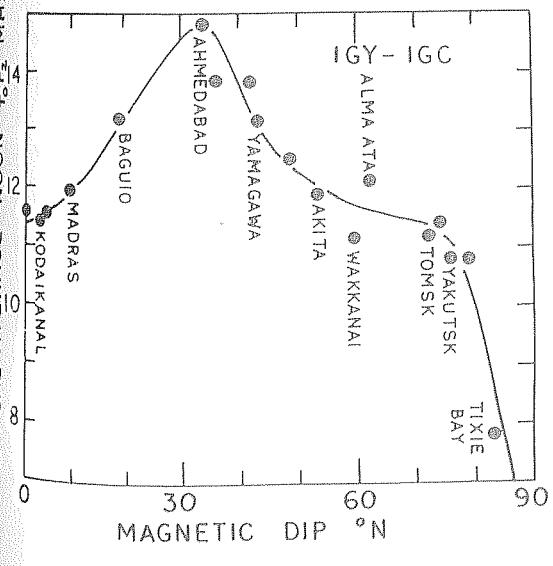


FIG. 2

Equatorial anomaly in noon f_0F_2 for Asian zone.

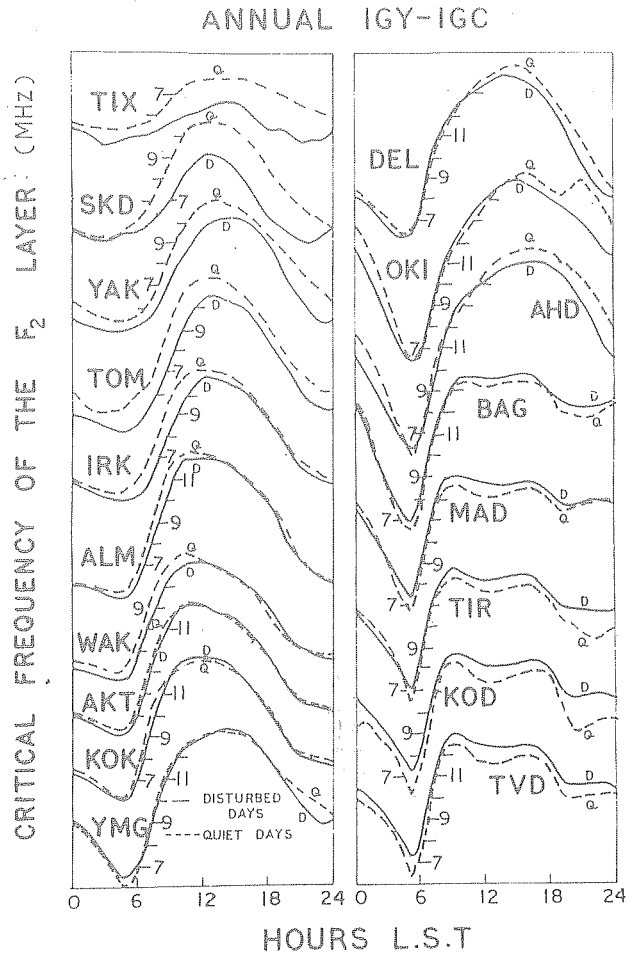


FIG. 3

Annual average solar daily variation of f_0F_2 at the different stations on Q and D days of IGY-IGC.

Figure 3 shows the IGY-IGC behaviour of solar daily variations on D as well as Q days for each of the stations. It is seen that at TVD and KOD which are closest to the magnetic equator, the values on D days are larger than the corresponding values on Q days, for any of the solar hours. The same is true at TIR, MAD and BAG, for most hours of the day. This confirms that at stations within the equatorial trough, at least in the daytime, magnetic disturbances cause an increase of f_0F_2 above the normal values. It is seen too, that normally, the maximum increase happens near midday, which is also the time of the well-known bite-out of f_0F_2 at equatorial stations. At AHM, OKI and DEL, the D values are smaller than the corresponding Q values for most of the hours except forenoon, and the maximum storm effect occurs in the evening. These observations indicate that the disturbance daily variation within these latitudes is just a modification of the daily development of the equatorial anomaly. At stations,

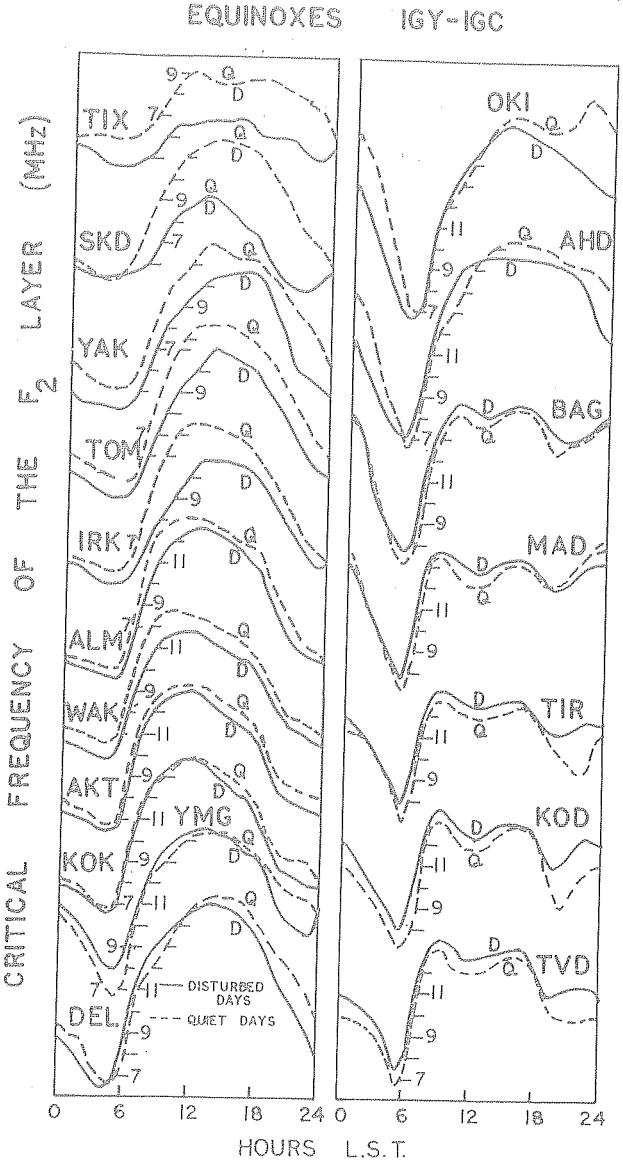


FIG. 4

Solar daily variation of f_0F_2 on Q and D days of Equinoxes of IGY-IGC.

YMG, KOK and AKT, there is little difference between Q and D days. A closer examination shows that D values are slightly less than Q values during night hours only. At WAK and ALM, this decrease is seen only between 00 hr. and 12 hr. At still higher latitude stations, D values are smaller than Q values for all hours of day and night. This picture in a qualitative way, confirms the generally understood behaviour, except that of the insignificantly small effect of magnetic disturbance at the Japanese stations.

Similar studies were made for each of the seasons separately to understand the disturbed behaviour.

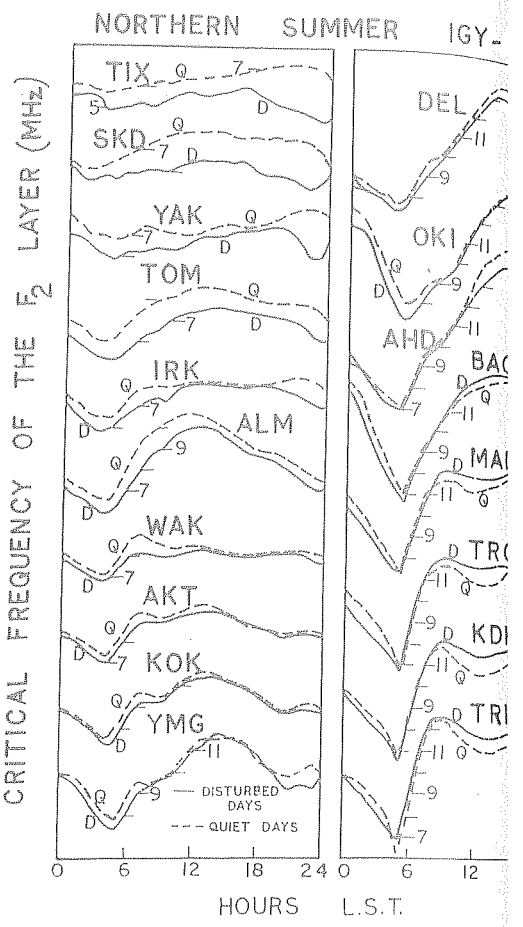


FIG. 5

Solar daily variations of f_0F_2 on Q and D da of June solstices (local summer) of IGY-IGC

Figure 4 shows these curves for the Eq D values are greater than Q for all hours a KOD and TIR, but for only daytime hours a and BAG. At AHM a reversal in dist behaviour occurs, with the D values being g smaller than Q values, for almost all hours and night.

The daily variations on Q and D days du June months are shown in Figure 5. The be at equatorial stations is similar to that d earlier. At stations above the latitude of A reversal in disturbance — behaviour occurs, as with the D values being generally smaller values, for almost all hours of day and night.

The variations during the December mon shown in Figure 6. Again at stations, TVD, TIR and MAD, D values are greater than Q for almost all hours, while at BAG, the D and Q of f_0F_2 are almost the same for most hours, for a few hours around 06 hr. and 22 hr. At OKI and DEL, D is less than Q for afterno

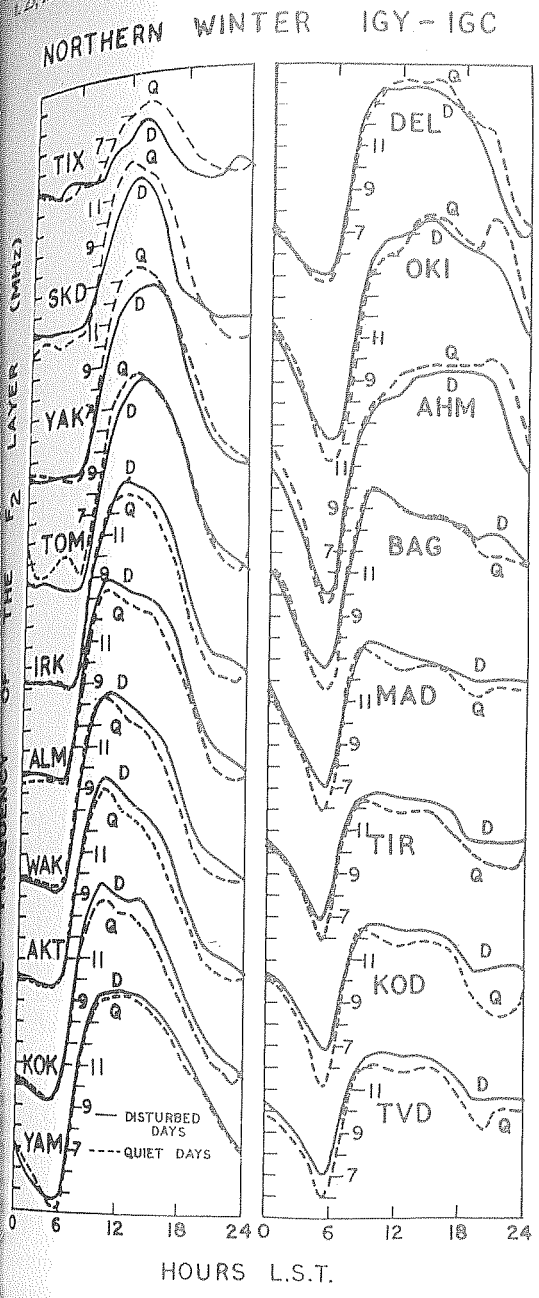


FIG. 6

Solar daily variations of f_0F_2 on Q and D days of December solstices (local winter) of IGY-IGC.

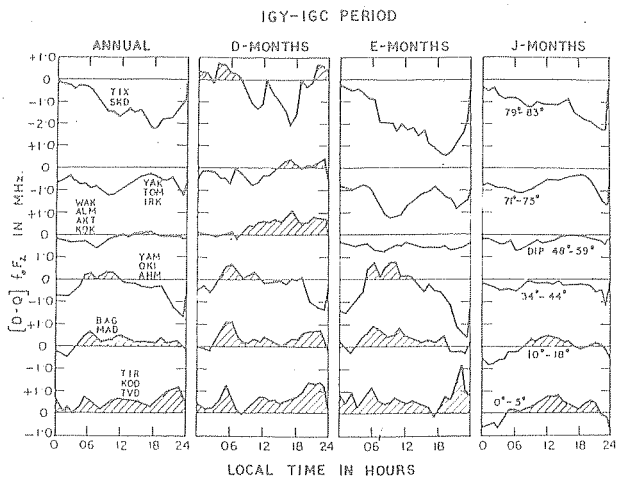


FIG. 7

Disturbance solar daily variation S_D (f_0F_2) for different seasons of IGY-IGC.

part of the night. At all the Japanese stations ell as at ALM and IRK, the D values are greater Q values, for most of the daytime and for the half of the night. This increase is rather pected. At higher latitude stations, D values gain less than Q values, at least for all daytime rs.

hose stations having similar variations have been grouped together, and the average difference of f_0F_2 on D and Q days have been shown in Figure 7 for six such groups during each of the seasons. The shaded portions denote excess of $D(f_0F_2)$ over $Q(f_0F_2)$. It is seen that at stations within 0° — 5° dip $(D - Q)$ f_0F_2 is positive for all hours, during D and E-months and for 5 hr. to 21 hr. during J-months. At stations between 10° and 18° the variations are similar except that the positive phase during June happens only during 09 hr. and 16 hr. At stations between 34°-44°, $(D - Q)$ f_0F_2, is positive between 05 hr. to 12 hr. during D and E-months, and is negative for all hours of day and night during J-months. At station between 48° — 59°, $(D - Q)$ f_0F_2 is negative for all hours during E and J months and is positive for hours between 09 and 24 hr. during D months. At still higher latitudes between 71° and 75° $(D - Q)$ f_0F_2 is more negative during E and J months and is slightly positive between 15 hr. and 24 hr. during D-months. At higher latitude stations between 79° — 83°, $(D - Q)$ f_0F_2 is strongly negative during the day and positive during the night for the D-months. During E and J-months, it is strongly negative for all hours.

Taken as a whole, the curves show that during the J-months, the positive phase of the ionospheric storms occurs between 0° — 18° dip, during E-months the positive storm-effect extends up to 44°, while during D-months, the positive phase of $(D - Q)$ f_0F_2 variation occurs at almost all latitudes, although the time of occurrence shifts uniformly from forenoon at low latitudes to night hours at high latitudes. This suggests that during the D-months, the ionospheric storm is affected by phenomena originating at the equator as well as at high latitudes.

To study the ionospheric disturbance in relation to the equatorial anomaly, the ratio, f_0F_2 on D days/f_0F_2 on Q days, as well as average f_0F_2 have

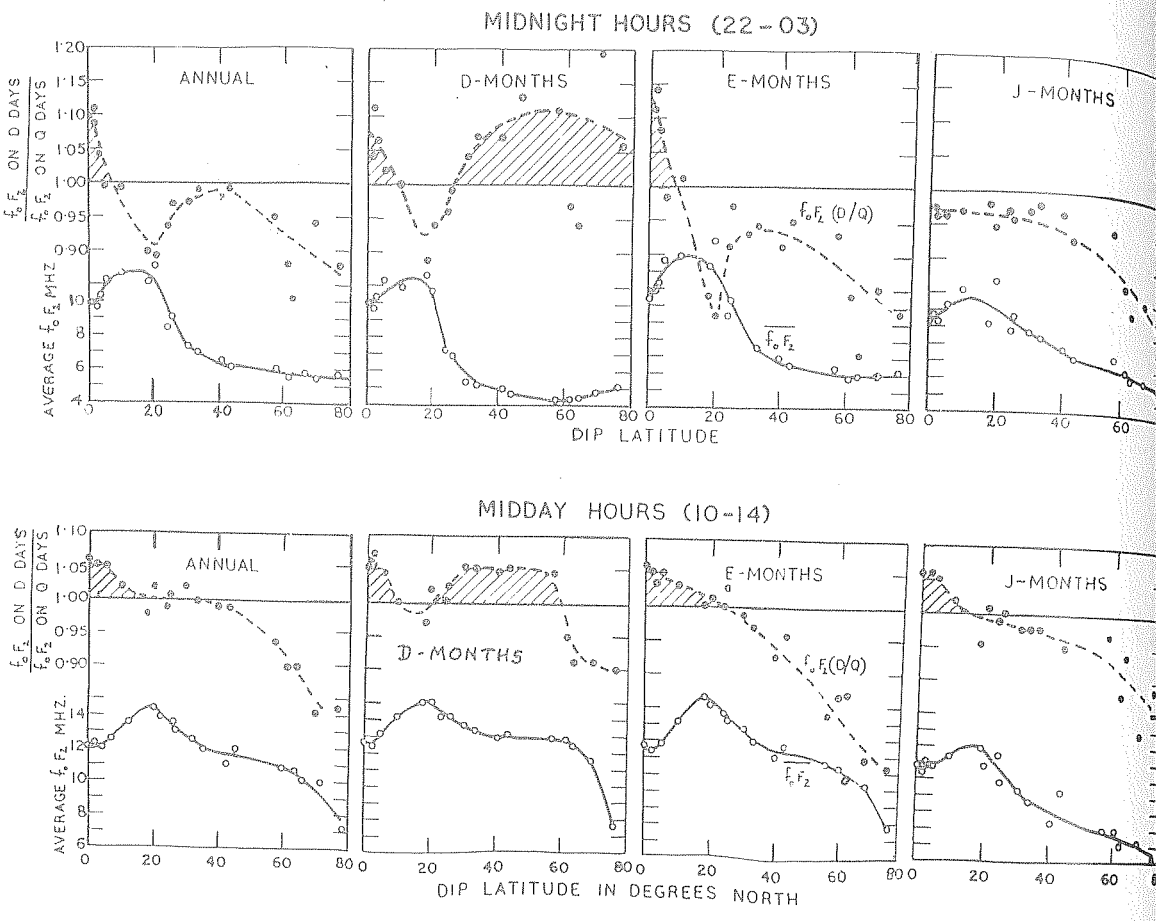


FIG. 8

Variation of average f_0F_2 and $\frac{D(f_0F_2)}{Q(f_0F_2)}$ with dip latitude for different seasons of IGY-IGC for mid-day and mid-nigh

. 25, fasc. 4, 1969

been plotted against dip latitude separately for mid-day hours (10 hr. — 14 hr.) and mid-night hours (22 hr. — 03 hr.). These are shown in Figure 8. Studying this relationship for the mid-day hours, it is seen that the annual average latitude variation of mean f_0F_2 shows the well-known peak at 20° dip latitude. The ratio $\frac{D}{Q}(f_0F_2)$ is greater than 1.0 below 20°; is almost equal to 1.0 between 20° and 35°, and decreases below 1.0 with further rise in latitude. Thus the change-over of the disturbance effect from positive at the equator to negative at high latitudes occurs at the region close to the tropical f_0F_2 peak. It is to be noted that phase reversal of lunar tide in f_0F_2 from equatorial type to high-latitude type occurs at 11° dip latitude which is almost half way between the equator and the tropical f_0F_2 peak. During the *J*- and *E*-months, the features are similar to that described above, the change-over of disturbance effect occurring at a latitude slightly below 20° during *J*-months, and slightly above 20° during *E*-months. The decrease of this ratio with latitude is much faster during *E*-months. During the *D*-months, the average F_2 shows a broad maximum around 60° dip latitude this is the winter spur referred to earlier. The ratio $\frac{D}{Q}(f_0F_2)$ is greater than 1.0 between 0° and 10° and also between 20° and 60°. This suggests that the positive effect of magnetic storms at mid-latitudes is associated with phenomena causing the winter spur.

Referring to the mid-night hours, one notices that e equatorial anomaly does exist during the mid-ght hours of the years under study, although the latitude peak is a sharper one. The annual erage $\frac{D}{Q}(f_0F_2)$ ratio is greater than 1.0 for a few grees near the equator. During the *J*-months, the io is less than 1.0 for any of the stations, and creases uniformly with increasing latitude. During nonths, the ratio is greater than 1.0 between – 5° latitude, and is less than 1.0 for higher lati-es. During *D*-months, it is less than 1.0 at a small ion around 20° latitude which is close to the peak region. At latitudes below 10° and above 20° ratio is greater than 1.0. Thus the abnormal urbed behaviour of f_0F_2 exists during both the -day and mid-night hours of the *D*-months.

m-time variation of $f_0F_2 - D_{st}$ (f_0F_2).

o further understand the disturbance behaviour, as decided to study the storm-time variations F_2 in this zone for the stations mentioned before. method of analysis is the superposed epoch one which the degree of disturbance — the ratio, n f_0F_2/ median f_0F_2 for the same hour — has averaged for 4 hours preceding the storm-commencement, and 72 hours following it. All the storms of the IGY-IGC period, with $A_p \geqq 50$ have been used in the analysis. As there are nearly 80 storms, it was assumed that the storms would be distributed evenly over the different times of the day, and hence the diurnal variation would disappear.

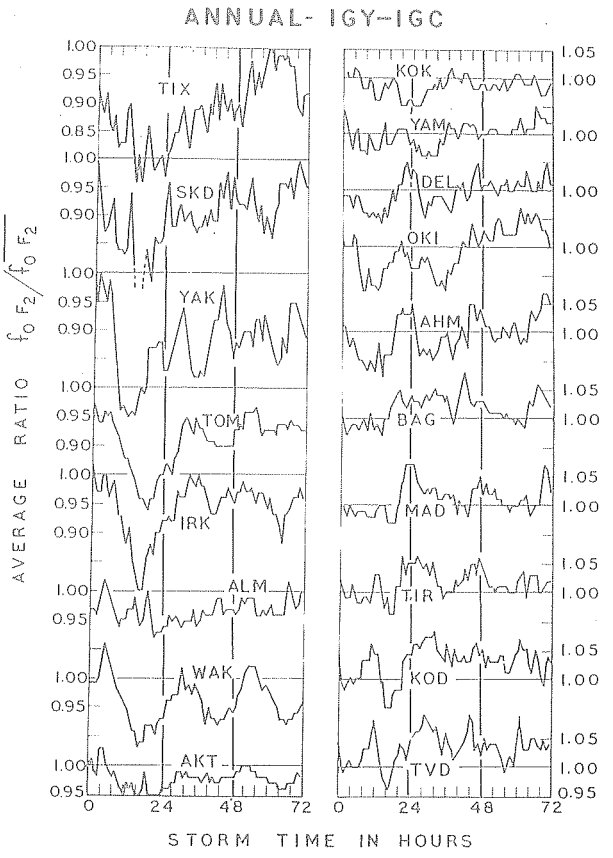


FIG. 9

Annual average D_{st} (f_0F_2) variation at different stations during IGY-IGC.

The annual average picture of these storm-time variations is given in Figure 9. This reflects the same behaviour as that of the annual $S_D(f_0F_2)$ variation, the ratio, storm f_0F_2/Median f_0F_2, during the main phase being greater than 1.0 upto BAG, and changing to less than 1.0, at higher latitudes. The ratio continues to decrease with increasing latitude. It is interesting to note the one-to-one correspondence of the predominant peaks, at almost all the latitudes. The strong 24-hour component at WAK may be due to a particular storm-time component showing itself strongly at this particular latitude. The stations, DEL, YAM, KOK and AKT seem to show very small amplitude of ratios as compared to the other stations.

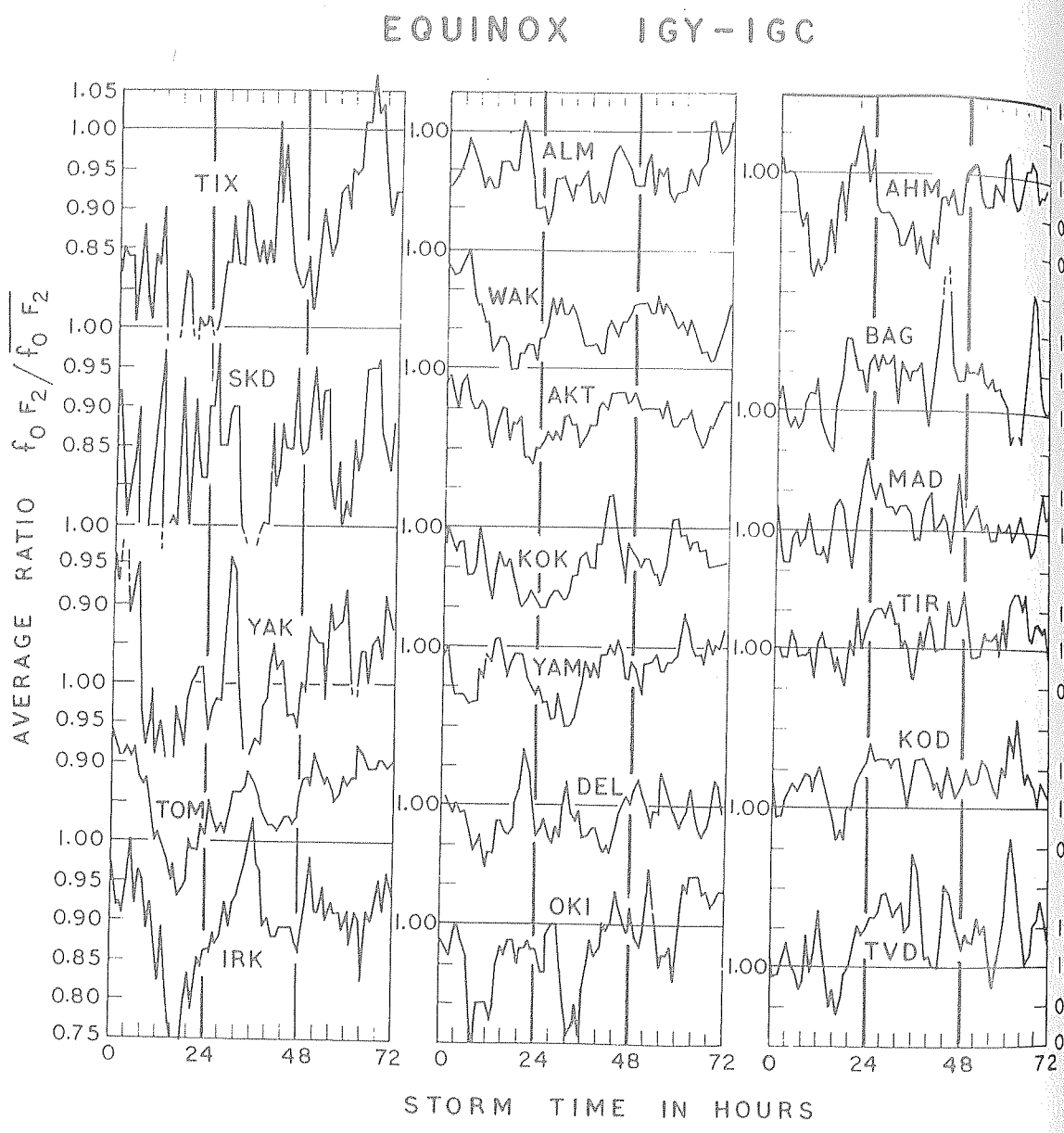


FIG. 10

D_{st} (f_0F_2) variation during Equinoxes of IGY-IGC.

Vol. 25, fasc. 4, 1969

The $D_{st}(f_0F_2)$ behaviour during the Equinoxes and June solstice is shown in Figure 10 and Figure 11 respectively. The change-over of the ratio, storm f_0F_2/median f_0F_2 from greater than 1.0 to less than 1.0 occurs north of BAG in the *E*-months, and almost at BAG in the *J*-months. This is similar to the annual average behaviour described above.

It is in the winter months that the picture changes, and this is shown in Figure 12. Here the equatorial stations, TVD, KOD, TIR and MAD clearly show values of storm f_0F_2/median f_0F_2 to be greater than 1.0 during the main phase. At BAG too, this is so. At stations, AHM, OKI and DEL, this ratio is rather uncertain, but higher north, right up to TOM at a dip of 74°, it is definitely greater than 1.0. Very high latitude stations, YAK, SKD and TIX of course show ratios less than 1.0. Thus the abnormality exhibited by $S_D(f_0F_2)$ in the winter months shows itself in $D_{st}(f_0F_2)$ variation too. Another point to be noted is the large amount of fluctuation in the curves for the winter months, which is remarkably absent in those for the summer months.

The effect of geomagnetic activity on the F_2 layer at stations in other zones is being studied.

Acknowledgment

The authors are grateful to Professor K. R. Ramanathan for his valuable discussions and suggestions during the course of the work.

Manuscrit reçu le 26 août 1969.

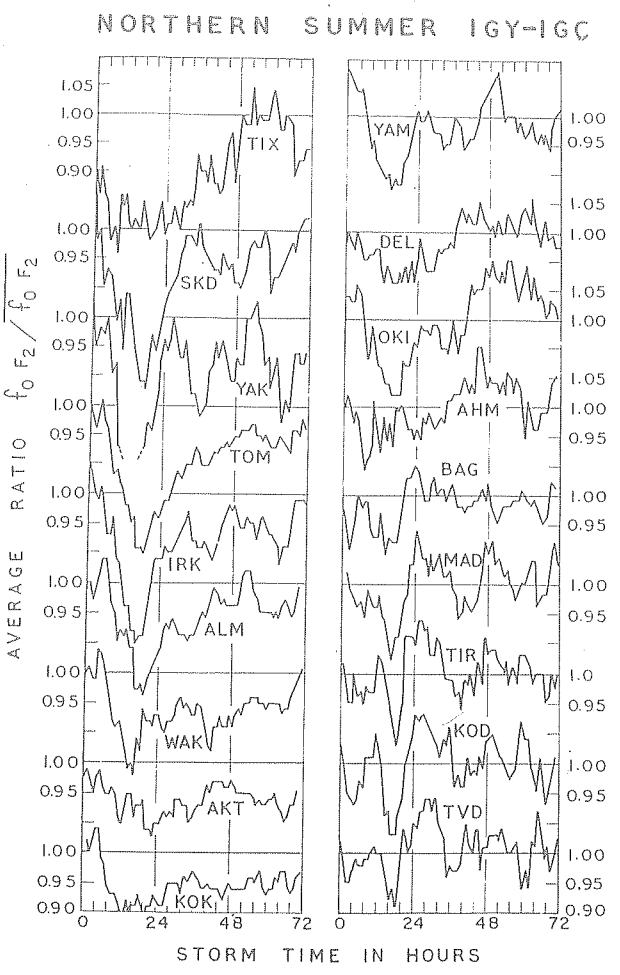


FIG. 11

D_{st} (f_0F_2) variation during June Solstices (local summer) of IGY-IGC.

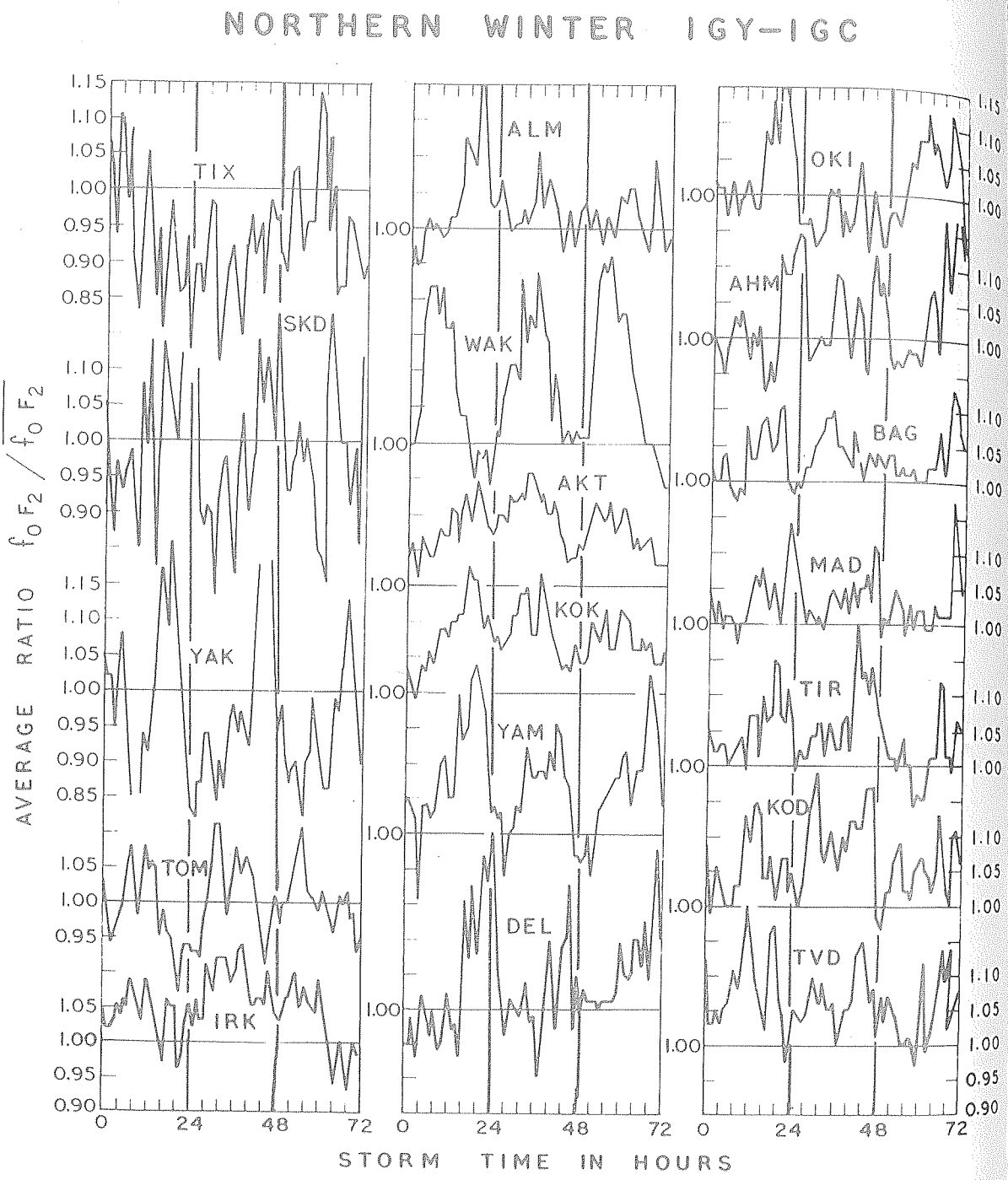


FIG. 12

D_{st} (f_0F_2) variation during December Solstices (local winter) of IGY-IGC.

, 25, fasc. 4, 1969

REFERENCES

APPLETON E. V. and INGRAM L. J., "Magnetic storms and upper atmospheric ionisation," *Nature*, Lond., 136, 548-549, 1935.

BERKNER L. V. and SEATON S. L., "Systematic ionospheric changes associated with geomagnetic activity," *Terr. Mag. and Atmos. Elec.*, 45, 419-423, 1940.

BHARGAVA B. N. and RAO U. V. G., "Ionospheric disturbances associated with magnetic storms at Kodaikanal," *Ind. Jour. of Met. and Geophys.*, 10, 203-208, 1959.

DOLGOVA YE. I., "Ionospheric — magnetic disturbances in years of maximum solar activity," *Geomag. and Aeronomy*, 5, 340-345, 1965.

FELDSHEYN NA. I. and ZAYTSEV A. N., "Disturbed S_D variations at high latitudes during the IGY," *Geomag. and Aeronomy*, 5, 367-374, 1965.

IONATOV V. S., "Disturbance of the ionosphere at the geomagnetic poles," *Geomag. and Aeronomy*, 2, 385-389, 1962.

KIYANOVSKIY and MEDNIKOVA N. V., "The relationship between geomagnetic and ionospheric disturbances at mid-latitudes," *Geomag. and Aeronomy*, 3, 622-624, 1963.

KOTADIA K. M. and RAMANATHAN K. R., "Effect of geomagnetic disturbances on F_2 layer of the ionosphere in low and middle latitudes," *Proceedings of IGY Symposium*, 1, 176-196, 1961.

MATSUSHITA S., "A study of the morphology of ionospheric storms," *Jour. Geophys. Research*, 64, 305-321, 1959.

MAEDA K. and SATO T., "The *F*-region during magnetic storms," *Proc. Inst. of Radio Eng.*, 47, 232-238, 1959.

MARTYN D. F., "Morphology of ionospheric variations associated with magnetic disturbances," *Proc. Royal Soc.*, A218, 1-18, 1953.

NAGATA T., "Ionospheric storms in high latitudes," *Rep. Ionos. Res. in Japan*, 8, 39-44, 1954.

OBAYASHI T., "On the world-wide disturbances in the F_2 region," *Jour. of Geomag. and Geoelec.*, 5, 41-50, and 6, 57-67, 1954.

RASTOGI R. G., "On the meridional transport of ionisations in the *F*-region of the ionosphere," Proc. of Symp. on Phys. Processes in sun-earth environment, Ottawa, July 20-21, 1959.

RASTOGI R. G., "Abnormal features of the F_2 region of the ionosphere at some southern high-latitude stations," *Jour. of Geophys. Research*, 65, 585-592, 1960.

RASTOGI R. G., "A Synoptic study of the F_2 region of the ionosphere in the Asian zone," *J. Atmosph. Terr. Phys.*, 18, 315-331, 1960.

SATO T., "Disturbances in the F_2 region of the ionosphere associated with geomagnetic storms," *Rep. of Ionos. Res. in Japan*, 10, 35-48, 1956.

SKINNER N. J. and WRIGHT R. W., "Some geomagnetic effects in the equatorial F_2 region," *J. Atmosph. Terr. Phys.*, 6, 177-188, 1955.

THOMAS J. O., "Electron density distribution in the F_2 layer of the ionosphere in winter," "Electron density distributions in the ionosphere and exosphere," p. 226, edited by Thrane, 1964.

THOMAS L. and VENABLES F. H., "The onset of *F*-region disturbance at mid-latitudes during magnetic storms," *J. Atmosph. Terr. Phys.*, 28, 599-605, 1966.

Paper 4

Indian Journal of Pure & Applied Physics
Vol. 8, September 1970, pp. 551-554

F-region Disturbances in the Australasian Zone during IGY-IGC

GIRIJA RAJARAM & R. G. RASTOGI
Physical Research Laboratory, Ahmedabad 9

A study of f_0F_2 in the east zone (i.e. Australasian zone) during magnetically disturbed conditions shows the existence of some asymmetry between the northern and southern hemispheres. During the day-time hours of the winter months, there is a prominent increase in $D/Q(f_0F_2)$, the ratio of disturbed to quiet values of f_0F_2, between 40°N and 70°N dip. Similar but rather a flatter hump is observed in the southern hemisphere in the day-time in the local winter months. These humps seem to get stronger during the night hours of the local winter months. The $D_{st}(f_0F_2)$ variations show an unexpected positive phase at the Japanese stations together with the region of reduced disturbed f_0F_2 values around 30° dip. The effect of storms on f_0F_2 seems more enhanced in the northern hemisphere than in the southern hemisphere. Within ±40° dip the disturbance effects in f_0F_2 are associated with the normal solar daily variation of f_0F_2, which in turn is controlled by the equatorial electrojet current.

THE effect of magnetic disturbances on the F-region of the ionosphere has been the subject of much investigation by workers all over the world since the earliest studies by Appleton *et al.*[1], who found a strong negative correlation between magnetic activity and the critical frequency of the F_2 layer at high latitude stations, Slough and Tromso. Berkner and Seaton[2] showed that the daily average electron density of F_2 at an equatorial station Huancayo increased continuously with increase of magnetic activity, whereas at a temperate latitude station Watheroo, the summer months showed a negative correlation between the two, and the winter months a positive correlation. Martyn[4] found that, during disturbances, there is a tendency for the electron density to be raised at low latitudes and lowered at high latitudes; at medium latitudes the mean values of f_0F_2 were depressed in summer and equinoxes, while the effect was much smaller in winter. Matsushita[5] studied the $D_{st}(f_0F_2)$ variations at a large number of stations round the world, grouping them into different geomagnetic latitude zones. He found that irrespective of the season, stations in the equatorial belt show a positive phase, and stations in the high latitudes a negative phase; in the intermediate zone, the variation resembled that for equatorial stations in winter, and high latitude stations in summer. Rastogi[6] showed that the effect of magnetic storms on f_0F_2 is governed by the dip angle of the station and not by its geographic or geomagnetic latitude.

In this paper, the results of a study of the effect of magnetic disturbances on F_2 critical frequencies separately, at stations in the east zone (i.e. the Australasian zone) between ±83° dip during the IGY-IGC period have been presented.

The solar daily variations of f_0F_2 on quiet (Q) and disturbed (D) days for both the D-months (November, December, January and February) and the J-months (May, June, July and August) at some of the stations are shown in Fig. 1. Kodaikanal is a typical equatorial station at which disturbed f_0F_2 always exceeds quiet f_0F_2, the effect being most pronounced during mid-day, thereby decreasing the noon bite-out of f_0F_2. Baguio (dip, 19°N) and Singapore (dip, 17°S) are in the transition region where the disturbance effects are rather small and uncertain. Ahmedabad (dip, 33°N) seems to lie in the region where disturbed f_0F_2 values are less than quiet f_0F_2 values in both seasons. It may be noted that the effect of the disturbances is most pronounced in the postsunset period when f_0F_2 value is normally greatest. No corresponding station is available in the south for comparison with Ahmedabad. Both Akita (dip, 53°N) and Watheroo (dip, 65°S) show the seasonal change-over of disturbed f_0F_2 values, from an enhancement in local winter to a decrease in local summer. Salekhard (dip, 79°N) and Hobart (dip, 72°S) lie in the high latitude region where disturbances decrease F_2 critical frequencies in all seasons. Thus, in the northern hemisphere, the latitude of change-over from the positive to the negative type of disturbed f_0F_2 varies appreciably with season. There seems to exist a trough at the mid-latitude region where disturbances always decrease f_0F_2 values irrespective of the season, and then a 'hump' at higher latitudes with increased f_0F_2 values during local winter. This hump disappears at the polar latitudes where disturbances decrease f_0F_2 at all seasons.

The variations with dip of the degree of disturbance in f_0F_2, i.e. the ratio f_0F_2 on D days and on Q days, are shown in Fig. 2 for the mid-day and mid-night hours of each season. The corresponding variation of the average f_0F_2 values are also shown on the diagrams. Thus, a comparison between the geomagnetic anomaly in f_0F_2 and the disturbance effect can be made. During any of the seasons, the noon bite-out at the equator, shown in average f_0F_2, is replaced by an enhancement of f_0F_2 during disturbed conditions. In the day-time of the

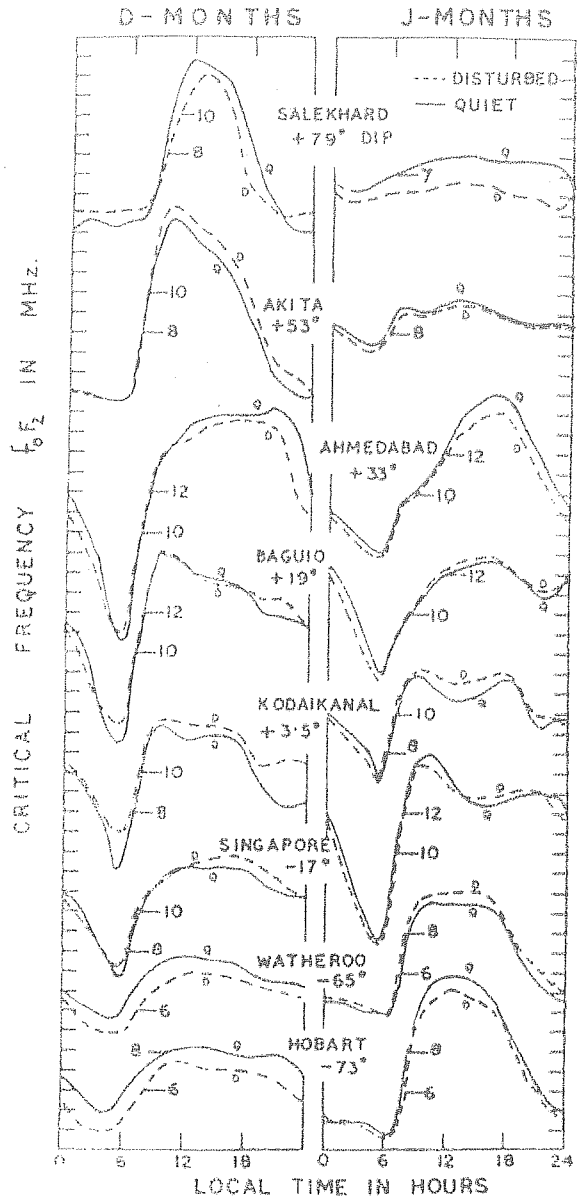


Fig. 1 — Solar diurnal variation of f_0F_2 on Q and D days, for northern and southern stations in the east zone

D-months, the $D/Q(f_0F_2)$ curve shows, apart from the equatorial enhancement, another enhancement between 40° and 70° dip with a minimum in between. This is shown to some extent in the average f_0F_2 in the ' spur ' occurring beyond 60° dip. In the night-time hours, the features in the D/Q variation mentioned above are even more enhanced, but all evidence of the spur in the average f_0F_2 curve vanishes. During the J-months, the $D/Q(f_0F_2)$ ratio is greater than unity for the day-time and less than unity during night-time. During the day-time the ratio $D/Q(f_0F_2)$ decreases continuously with latitude in the northern hemisphere while in the southern hemisphere a hump around 60° is seen with a trough around 30°. Thus, the day-time behaviour in the S and N hemispheres is similar in the same local season. During the night a southern hump at 60° is seen with no trough around 30°. Thus, the night-time behaviour differs between N and S hemispheres primarily due to the decrease of f_0F_2 at the equator during the J-months while an increase occurs during the D-months. Fig. 3 shows the annual average $D_{st}(f_0F_2)$ variation (the storm-time variation of f_0F_2) for the east zone. About 80 strong storms, i.e. storms with A_p exceeding 50 on any of the 3 days following the commencement of the storm, of the IGY-IGC period have been averaged to obtain the average ratio $f_0F_2/\overline{f_0F_2}$ (i.e. storm value of f_0F_2 at a particular hour/median f_0F_2 for the same hour) for each of the 72 hr following the storm. Pairs of stations of approximately same dip N and S have been used for this study. Trivandrum and Kodaikanal as typical equatorial stations show chiefly a positive phase (i.e. values of these ratios are greater than 1·00). Singapore and Baguio with dip of about 18° show mainly positive values between 24 and 48 hr storm-time. Townsville and Akita are mid-latitude stations, and show an uncertainty in the variation. A feature worth noticing is the pronounced 24 hr repetition frequency of the ratio peaks at Townsville. Brisbane and Wakkanai lie in the higher latitude region, and show a negative phase (i.e. values of the ratio are less than 1·00). Wakkanai shows the repetitive 24 hr period ratio-peaks. The pairs of stations Canberra-Alma Ata and Hobart-Irkutsk have clearly negative peaks. Ratio values for Canberra are lower than for Alma Ata and ratios for Hobart are lower than those for Irkutsk. A sharp dip in ratios around 24 hr storm-time characterizes both Hobart and Irkutsk; Scott Base and Tixie Bay both have the very high value of dip of 83°, and show clear negative phase marked by rapid ratio fluctuations. This is probably a polar region effect, and may be related to the periodic dumping-in of charged particles along the favourably aligned geomagnetic lines of force. Taken on the whole, Fig. 3 shows that the storm-time variations follow approximately the same N and S pattern except for slight differences in the mid-latitude regions.

Fig. 4 shows the $D_m(f_0F_2)$ variation with dip N and S. This is the mean of the ratios $f_0F_2/\overline{f_0F_2}$ taken over 00-48 hours. It represents the net effect on F_2 critical frequencies of the storm-time ring-current (DR) which is supposed to encircle the earth at a distance of about 4 earth radii. This is shown for the D-, E- and J-months in Fig. 4.

The ring-current effects in the E-months show a fair symmetry in the variation in the N and S hemispheres. The annual picture is much the same. In the D-months, the ring-current appears to cause enhancements of $D/Q(f_0F_2)$ in the equatorial and northern high latitudes with a trough in between. In the J-months the equatorial enhancement is not pronounced, but there does seem to be an enhancement of ratios around 60° dip. Whether there is a trough of lesser ratios around 30° dip cannot be ascertained owing to the absence of an operating station in this critical region during IGY-IGC. The enhancement of these disturbance ratios in local winter is certainly more in the northern hemisphere than in the southern hemisphere.

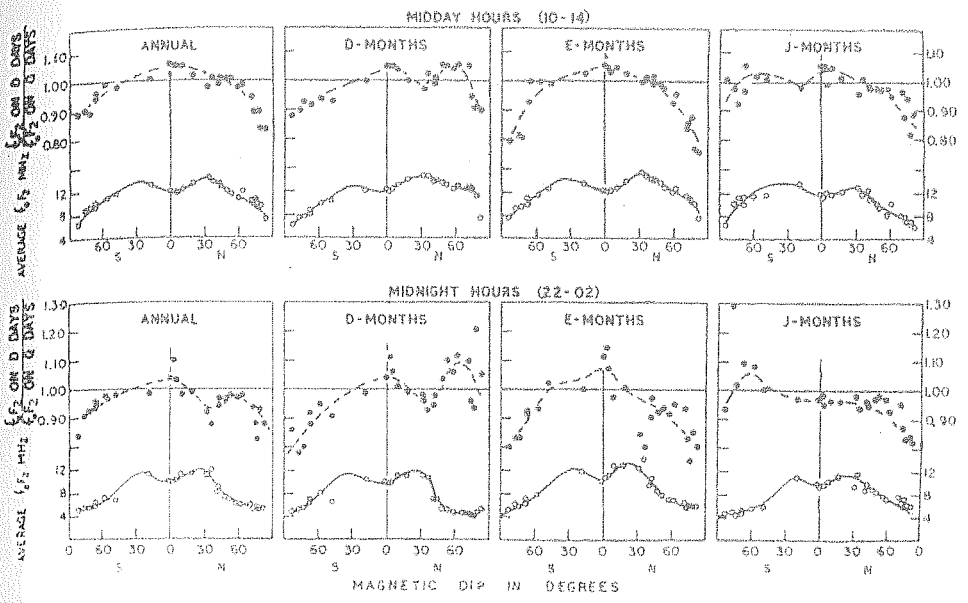


Fig. 2 — Variation of D/Q(f_0F_2) and average f_0F_2 with dip angle for day-time and night-time hours

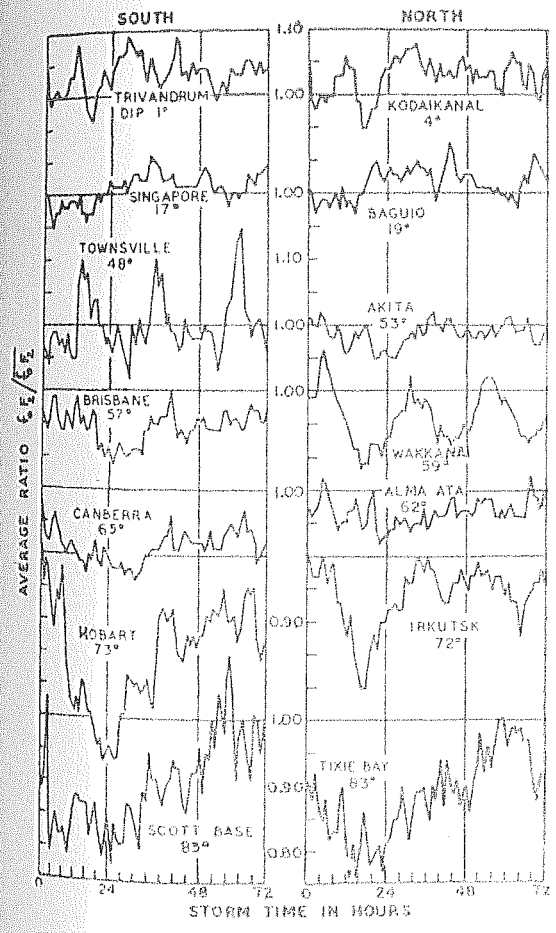


Fig. 3 — $D_{st}(f_0F_2)$ variations for northern and southern dip-conjugate stations in the east zone

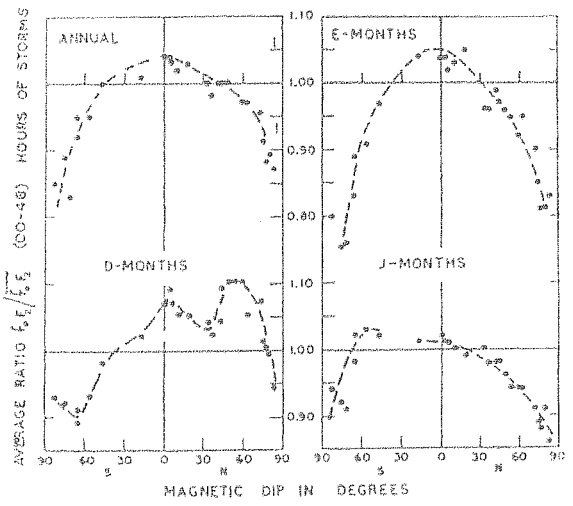


Fig. 4 — Variation of mean value of the ratio $f_0F_2/\overline{f_0F_2}$ during main phase of storms, with dip angle

Conclusion

The enhancement of disturbed f_0F_2 values in the equatorial region seems to be associated with a weakening of the equatorial electrojet current during geomagnetic disturbances. This is suggested by the decrease of the mid-day bite-out in f_0F_2 observed at equatorial stations on D days as compared to Q days. Further, the disturbance effect (decrease during disturbance) at tropical peak f_0F_2 regions is most pronounced during the evening hours. These two features are complementary to each other. A decrease of the electrojet would mean a smaller $(E \times B)$ lifting force on the F-region

ionization at the equator resulting in the decreased bite-out. Consequently, there is less transport of ionization along the geomagnetic lines of force to the mid-latitudes, resulting in lesser f_0F_2 at these latitudes on the D than on the Q days. This is also supported by the flattening of the F_2 geomagnetic anomaly crests on D days as compared to Q days.

The high latitude 'hump' of disturbed f_0F_2 around 60° dip in the winter hemisphere may be associated with the preferential precipitation of charged particles into the auroral zone. It is well known that the auroral belt shifts equatorward during geomagnetic disturbances. Its appearance only in the winter hemisphere bears a resemblance to the 'spur' occurrence mentioned by Thomas[7]. Why this does not happe summer hemisphere is rather puzzling. investigation of this problem is being car

References

1. Appleton, E. V., Naismith, R. & Ingram, I *Trans. R. Soc.*, A236 (1937), 191.
2. Berkner, L. V. & Seaton, S. L., *Terr. Ma Elect.*, 45 (1940), 419.
3. Appleton, E. V. & Piggott, W. R., *Physics o sphere* (Physical Society, London), 1955, 2
4. Martyn, D. F., *Nature, Lond.*, 171 (1953), 14.
5. Matsushita, S., *J. geophys. Res.*, 64 (1959), 3
6. Rastogi, R. G., *J. geophys. Res.*, 67 (1962), 1
7. Thomas, J. O., Electron density distributions i sphere and exosphere, *Proceedings of the NAT Study Institute, Norway, April* 1963, edited by (North Holland Publishing Co., Amsterdam),

Ann. Géophys., t. 27, fasc. 3, 1971, p. 359 à 367.

Paper 5

A synoptic study of the Disturbed Ionosphere during IGY-IGC (2) The American Zone

by (Mrs) Girija RAJARAM and R. G. RASTOGI,

Physical Research Laboratory
Ahmedabad-9, India.

RÉSUMÉ. — *Cette étude est la suite de notre article antérieur sur les perturbations de la région F2 dans la zone asiatique (réf. 1). Une étude détaillée du comportement de f_0F_2 en fonction de Dst et de SD pour des stations individuelles dans la zone américaine qui s'étend de l'inclinaison 89 °N à 75 °S a mis en évidence certaines anomalies dans le comportement connu des perturbations. L'étude des effets saisonniers montre l'existence d'un rapport D/Q (f_0F_2) accru aux moyennes latitudes en hiver plus fort de nuit que de jour et plus élevé que le rapport correspondant à l'équateur. Ce « pic » est plus large dans la zone Sud-américaine et semble associé à l'anomalie géomagnétique observée dans cette région.*

ABSTRACT. — *This study is a sequel to our previous paper on the F_2 disturbance effects in the Asian Zone (Ref. 1). A detailed investigation of the D_{st} (f_0F_2) and S_D (f_0F_2) behaviour for individual stations in the American zone ranging from 89° N dip to 75° S dip has brought out some anomalies in the known behaviour of disturbance effects. Seasonal categorisation shows the existence of an enhanced ratio of D/Q (f_0F_2) in the winter middle latitudes, stronger by night than by day, and stronger than the corresponding ratio at the magnetic equator. This 'peak' is larger in the southern American zone, and seems to be associated with the geomagnetic anomaly observed in this region.*

INTRODUCTION

The earliest studies of the ionospheric changes following a magnetic storm were generally of individual stations. Matsushita [1959] described the ionospheric storms at a large number of ionospheric stations grouping them into different geomagnetic latitude zones. It has been shown that the behaviour of ionospheric storms at low latitudes is governed by the actual magnetic dip of the station rather than by its geomagnetic latitude [RASTOGI, 1962]. Significant longitudinal differences have been shown to exist in ionospheric disturbances during the IGY-IGC period by Rastogi and Rajaram [1965]. With these points in view, a study of ionospheric storms for different seasons was undertaken; the results for the stations in the Asian Zone have been described in an earlier paper by Rajaram and Rastogi [1969]. This paper shall, henceforth, be referred to as Ref. 1.

The present paper describes the results of a study of ionospheric storms during the IGY-IGC period at stations situated over the complete American zone. The method of analysis is the same as in the earlier papers. The list of stations chosen for the analyses with their geographic and magnetic co-ordinates, as also their alphabetical abbreviations which have

been used in the paper are given in Table I. The positions of these stations with respect to the isodip lines are shown on the map in Figure 1. It can be seen that most of the stations lie in the longitude belt 45 °W to 105 °W and thus cover the complete latitude range from 89 °N dip to 75 °S dip; the southernmost station South Pole (75 °S dip and 90 °S geographic) could not be depicted on the map. It may be noted that the isodip lines have a strong tendency to show a convexity to the south; this is more marked in the southern hemisphere. In this respect this zone differs from the Australasian zone where the isodip lines are almost parallel to the lines of constant geographic latitude.

The Annual Average midday values of f_0F_2 plo against the dip angle of the stations are shown Figure 2. The equatorial anomaly is clearly see the diagram, HUA, LAP and TAL being situ within the anomaly trough; PMR and PAN lie close to the northern crest, and TUC, SAO lie to the southern crest of the anomaly. Beyond crests there is a gradual and steady decrease of towards the poles, and stations with dips gre than 30° lie on these declines. It may be seen the high-latitude 'spur' [THOMAS, 1964] which prominent at a latitude of 70° — 80 °N dip in Asian zone (Ref. 1, Fig. 2) is not clearly defined the American zone. It may also be noted that

TABLE I

Station	Abbreviation	Geographic		Magnetic	
		Latitude	Longitude	Dip.	Latitude
Res Bay.....	RES	74° 41′ N	94° 55′ W	+ 89°	88°
Eureka	EUR	80° 00′ N	85° 56′ W	+ 89°	86°
Baker Lake	BAK	64° 19′ N	96° 01′ W	+ 86°	82°
Churchill.....	CHR	58° 46′ N	94° 10′ W	+ 84°	78°
Winnipeg	WIN	49° 54′ N	97° 24′ W	+ 78°	66°
Ottawa	OTT	45° 24′ N	75° 54′ W	+ 75°	62°
St-Johns	SJO	47° 32′ N	52° 47′ W	+ 72°	57°
Washington	WAS	38° 44′ N	77° 08′ W	+ 71°	56°
San Francisco	SFR	37° 26′ N	122° 10′ W	+ 62°	43°
Whitesands	WHT	32° 18′ N	106° 30′ W	+ 60°	41°
Grand Bahama ..	GBH	26° 40′ N	78° 22′ W	+ 60°	41°
Puerto Rico	PUE	18° 30′ N	67° 10′ W	+ 51°	32°
Panama	PAN	09° 24′ N	79° 54′ W	+ 37°	21°
Paramaribo	PMR	05° 49′ N	55° 13′ W	+ 33°	18°
Bogota	BOG	04° 32′ N	74° 15′ W	+ 32°	17°
Talara.....	TAL	04° 34′ N	81° 15′ W	+ 13°	7°
Huancayo	HUA	12° 03′ S	75° 20′ W	+ 2°	1°
La Paz	LAP	16° 29′ S	68° 03′ W	— 5°	— 2°
Sao Paulo	SAO	23° 33′ S	46′ 38′ W	— 23°	— 12°
Tucuman.....	TUC	26° 53′ S	65° 23′ W	— 22°	— 12°
Buenos Aires.....	BNA	34° 36′ S	58° 29′ W	— 31°	— 17°
Concepcion	CON	36° 35′ S	72° 59′ W	— 36°	— 20°
Pt. Stanley.....	PST	51° 42′ S	57° 51′ W	— 46°	— 27°
Pt. Lockroy.....	PLO	64° 50′ S	63° 31′ W	— 58°	— 39°
Ellsworth	ELL	77° 43′ S	41° 08′ W	— 66°	— 49°
S. Pole	SPO	90° 00′ S	0° 0′	— 75°	— 62°

CAPTION : Stations studied in the American zone with the abbreviations used, and their geographic and magnetic coordinate

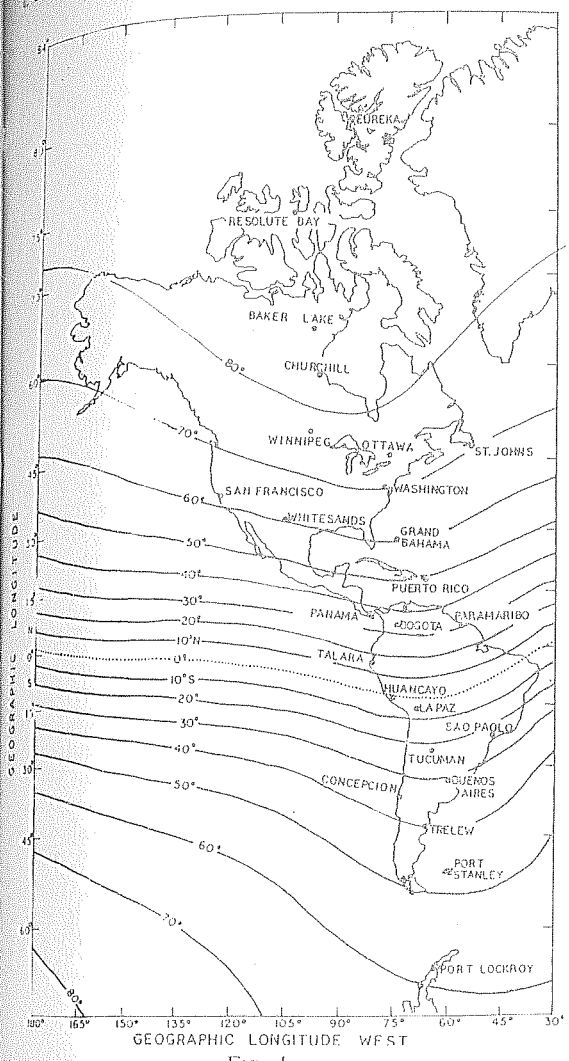


FIG. 1

Map showing the geographic and magnetic dip angle locations of stations in the American zone.

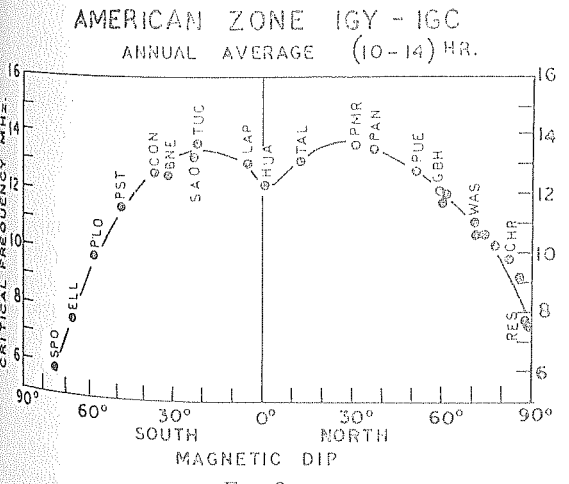


FIG. 2

Equatorial anomaly in noon f_0F_2 for the American zone.

critical frequencies outside the anomaly region are lower in the southern hemisphere than at a corresponding latitude in the northern hemisphere. This may be due to the abnormal distribution of the geomagnetic field, and its associated effects on the transport of electrons from the equator to the mid-latitude regions [RASTOGI, 1960].

DISTURBANCE SOLAR DAILY VARIATION $S_D(f_0F_2)$

The annual average daily variation of f_0F_2 on the five International Quiet (Q) and five International Disturbed (D) days of the IGY-IGC period are shown in Figure 3 for each of the stations. The full lines indicate the $D(f_0F_2)$ variations as compared to the dotted curves which indicate the $Q(f_0F_2)$ variations. In the paragraphs which follow the figures in brackets given against the stations refer to the dip angle of the station, + indicating North and — indicating South. At the equatorial stations, TAL, HUA and LAP, f_0F_2 is greater on D than on Q days for any

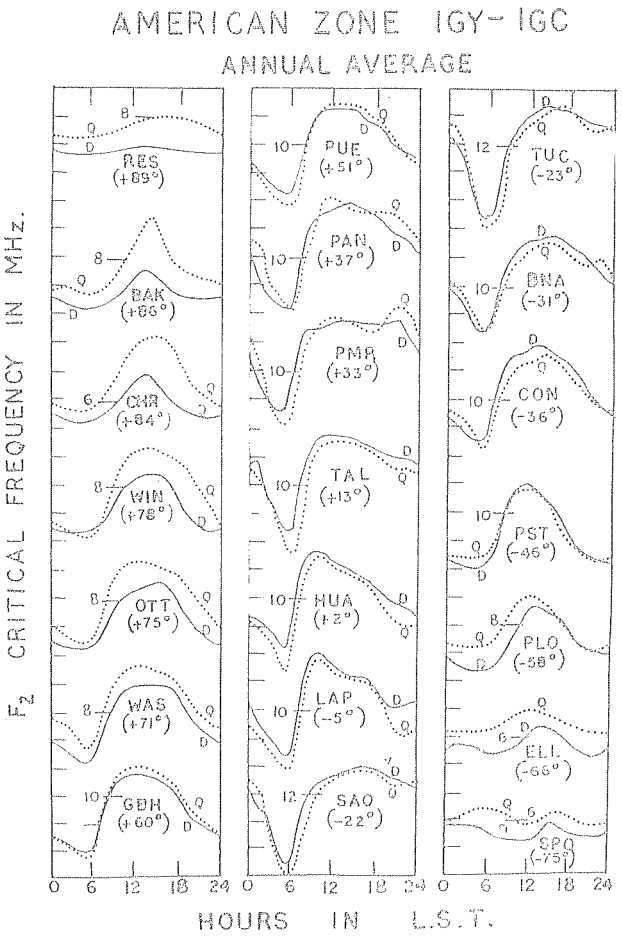


FIG. 3

Annual average solar daily variation of f_0F_2 at different stations on Q and D days of IGY-IGC.

hour of the day. The change-over region in the north occurs at PMR and PAN (about + 35°); here the difference between $D(f_0F_2)$ and $Q(f_0F_2)$ is uncertain. Beyond + 65° till + 89° all stations show $D(f_0F_2)$ less than $Q(f_0F_2)$, for all hours of the day, the difference between the two getting larger with increasing latitude. In the southern hemisphere, day-time f_0F_2 is greater on D than on Q days, even at non-equatorial stations SAO, TUC, BNA, and CON, which are close to, or just outside the southern anomaly crest. PST (— 46°) could be regarded as a change-over region showing uncertainty between $D(f_0F_2)$ and $Q(f_0F_2)$. Further south, PLO, ELL and SPO shows $D(f_0F_2)$ less than $Q(f_0F_2)$ though the difference is not as much as for the corresponding high latitude stations in the northern hemisphere.

The seasonal behaviour of $D(f_0F_2)$ and $Q(f_0F_2)$ for these stations is shown in Figure 4. Considering first the D-months (November, December, January and February) one finds that at the equatorial stations TAL, HUA and LAP, f_0F_2 around midday is lower on D than on Q days. This behaviour is different from that shown by the equatorial stations in the African and Asian zones, where midday f_0F_2 on D-days is greater than on Q days for all seasons [RASTOGI and RAJARAM, 1965]. In the northern hemisphere $D(f_0F_2)$ is greater than $Q(f_0F_2)$ within a small dip region around PUE and GBH (+ 60°).

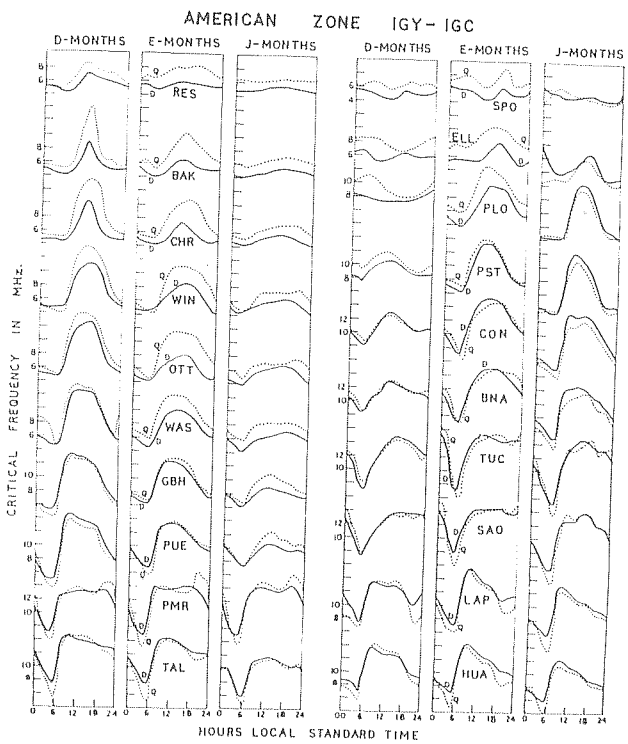


FIG. 4

Solar daily variation of f_0F_2 on Q and D days of the D-months, E-months, and J-months of IGY-IGC.

Beyond this, right till RES (+ 89°) $D(f_0F_2)$ is than $Q(f_0F_2)$, once again the decrease in $D(f_0$ increasing with increasing dip. In the sou hemisphere too, there is a narrow region around S and TUC (— 22°) where $D(f_0F_2)$ is greater th $Q(f_0F_2)$. The stations BNA (— 31°) and CO (— 36°) show an uncertainty, but beyond this SPO (— 75°), $D(f_0F_2)$ is less than $Q(f_0F_2)$, a expected of high-latitude stations. It may be not that the high latitude stations of the northern he sphere (winter hemisphere) show a sharper diur variation of f_0F_2 than the high-latitude stations the summer hemisphere (southern hemisphe (*Antarctic* Research Series, Vol. 4, 1965). A po worth noticing for the high-latitude stations is th in the northern hemisphere the maximum differe between $D(f_0F_2)$ and $Q(f_0F_2)$ occurs in the d time hours when $Q(f_0F_2)$ itself attains its highe value. In the southern hemisphere the differe between $D(f_0F_2)$ and $Q(f_0F_2)$ is maximum at mi when $Q(f_0F_2)$ here attains its highest values.

Considering the E-months (March, April, Septemb and October), the equatorial stations LAP, HU TAL show the expected $D(f_0F_2)$ greater than (f_0F_2). In the northern hemisphere the change-ov occurs at PMR (+ 33°). At all higher latitude st tions upto RES (+ 89°) $D(f_0F_2)$ is less than $Q(f_0$ In the southern hemisphere, the change-over regi is rather broad with TUC, BNA and CON all show some uncertainty; in fact at CON (— 36°), $D(f_0$ is greater than $Q(f_0F_2)$. Beyond this, till SP (— 75°) $D(f_0F_2)$ is less than $Q(f_0F_2)$. It may noted that the difference between $D(f_0F_2)$ and (f_0F_2) is less for the southern high-latitude stati than for the northern high-latitude stations; al the abnormal daily variation of f_0F_2 observed at ELL and PLO in winter, with night f_0F_2 exceeding da time f_0F_2 is absent in the equinoxes. The po sunset increase of f_0F_2 at around 33 °N dip a 33 °S dip remains. This has been attributed to th mal cooling of electrons arising from collisions [Eva 1965]. The character of the f_0F_2 variation cur in the N and S hemisphere does not differ much the equinoxes, there being no flat variations anywh this suggests that any ionisation locally produced the equator in the equinoxes directly under su influence is symmetrically distributed between two hemispheres.

Considering the J-months (May, June, July August), the equatorial stations, LAP, HUA, and T all show the expected $D(f_0F_2)$ greater than $Q(f_0$ In the northern hemisphere all stations north of region show $D(f_0F_2)$ less than $Q(f_0F_2)$. In southern hemisphere SAO (— 23°) and TUC (— show an uncertainty, while BNA, CON, PST, P and ELL (— 66°) all clearly show $D(f_0F_2)$ gre than $Q(f_0F_2)$. Nowhere right uptil this region + 66° dip does any station show $D(f_0F_2)$ less th $Q(f_0F_2)$ as expected of high-latitude stations.

at the southernmost station SPO (—75° dip) one cannot definitely say that $D(f_0F_2)$ is less than $Q(f_0F_2)$, there existing an uncertainty between the two. In this respect the South American zone differs from the North American zone in which the high-latitude decrease of $D(f_0F_2)$ is clearly shown in all seasons from WAS (+ 71°) to RES (+ 89°).

In the southern hemisphere only SPO (— 76°) retains its flat diurnal variation of f_0F_2. None of the northern high-latitude stations show the abnormal feature of maximum f_0F_2 occurring at night as was seen in some of the southern stations in the corresponding season.

Also, the difference between $D(f_0F_2)$ and $Q(f_0F_2)$ is more in the northern hemisphere than in the southern hemisphere; in the southern hemisphere itself this difference is larger in the D and E months and less in the J months. This suggests that the South American zone seems to experience enhanced electron densities during magnetically disturbed conditions, particularly in the local winter months.

In Figure 5 is shown the average difference of f_0F_2 between D and Q days for the different hours of the day for the different seasons. Stations having similar variations of f_0F_2 have been grouped together giving total coverage from north to south in 10 dip zones as shown in the diagram. The shaded portions denote excess of $D(f_0F_2)$ over $Q(f_0F_2)$.

Considering the variation of $(D - Q)f_0F_2$, in the dip zone (0° — 5°) S — i.e. at equatorial latitudes, the value of $(D - Q)f_0F_2$ is higher in the night than at day, in each of the seasons. This is so especially in the D months when there are negative midday values of $(D - Q)f_0F_2$; this implies that the effect of disturbances in this zone in this season has been to decrease f_0F_2 as compared to the quiet day values. This is an unusual feature for the equator. Almost the same observations hold for the dip zone 13 °N though here the values of $(D - Q)f_0F_2$ in the J months is slightly smaller than in the previous zone. The negative midday values of $(D - Q)f_0F_2$ during D months again may be noted. In the dip zone, 31° — 37 °N, negative values occur in the night hours, and in the D-months higher values of $(D - Q)f_0F_2$ are centred around the sunrise and sunset hours, with comparatively smaller values around midday. The second peak centred around sunset disappears in the E-months, and the one centred around sunrise too almost vanishes in the J-months. In the dip zone (51°-61 °N) negative values characterise both E and J months, and positive values occur at all hours in the D months. The higher dip zones (70°-77°) N and (82°-89°) N experience negative values of $(D - Q)$ f_0F_2 at all hours at all seasons. The maximum value of $(D - Q)f_0F_2$ at these latitudes seems to occur in the day-time rather than at night.

Considering the southern hemisphere, in the dip zone (22° — 23°) S, the maximum values of $(D - Q)$ f_0F_2 occur at around sunrise in the E and J months,

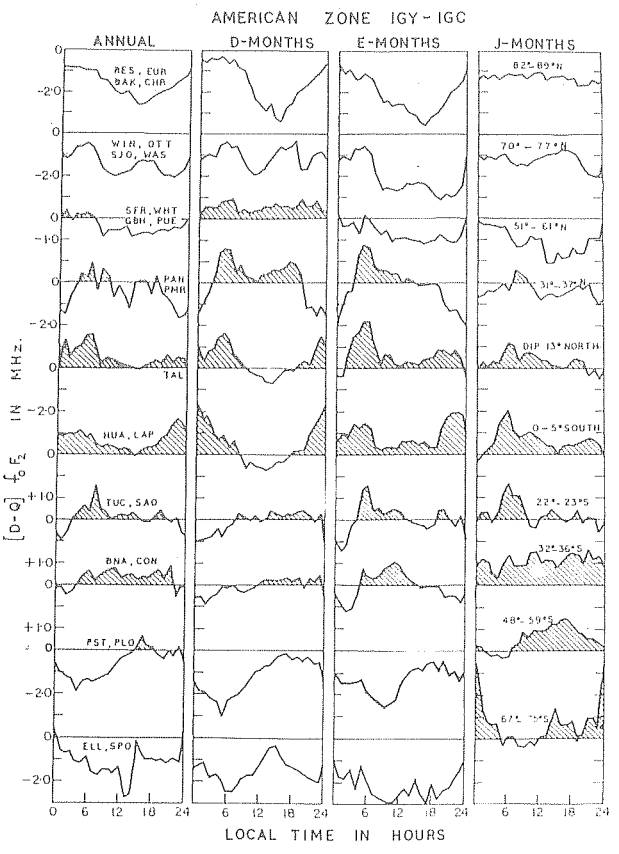


FIG. 5

Disturbance solar daily variation $S_D(f_0F_2)$ for different seasons of IGY-IGC for different dip zones of the American zone.

and in the D-months, only a small positive region of $(D - Q)f_0F_2$ occurs after 12 hours L.T. Much the same is true of the (32°-36°) S zone, only in the J-months, highly positive values of $(D - Q)f_0F_2$ persists through the (48°-59°) S zone, to the southernmost (67°-75°) S zone, though in this last, the maximum values of $(D - Q)f_0F_2$ occur in the night-time hours. The last two zones are marked by negative values of $(D - Q)f_0F_2$ in the D months and the E months.

To summarise all this, in the northern hemisphere the positive phase of $(D - Q)f_0F_2$ occurs upto (51°-61°) N dip in the D-months, to (31°-37°) N in the E-months, and only till dip 13 °N in the J-months. In the S hemisphere some positive phase occurs till 32°-36 °S in the D and E months, but continues right upto (67°-75°) S in the J-months.

The mean value of $D(f_0F_2)/Q(f_0F_2)$ for the midnight hours (22-02) and for the midday hours (10-14), as also the average f_0F_2 for the corresponding hours, are plotted against magnetic dip in Figure 6. This was done with a view to study the disturbance f_0F_2 effect in relation to the normal equatorial anomaly.

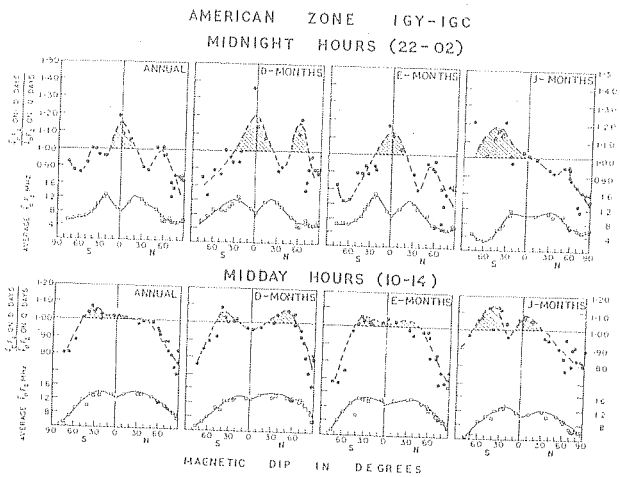


FIG. 6

Variation of average f_0F_2 and $D(f_0F_2)/Q(f_0F_2)$ with magnetic dip for different seasons of IGY-IGC for mid-day and mid-night hours.

Considering the *D* months in the midday hours, the ratio $D/Q(f_0F_2)$ is less than 1.00 between $\pm 20°$ dip giving a decrease in f_0F_2 during disturbed conditions even at the equator where normally only an increase is expected. This is unusual. Positive regions of $D/Q(f_0F_2)$ occur around 40° dip both N and S, these peaks occurring at higher dip value than the normal f_0F_2 anomaly crests. Beyond 60° dip, the ratio $D/Q(f_0F_2)$ falls off below 1.00 gradually with increase in dip. In the night the equatorial trough of $D/Q(f_0F_2)$ is filled up and replaced by a positive peak, the southern peak disappears, while the northern peak around 60° dip becomes narrower and sharper. A mid-latitude trough in $D/Q(f_0F_2)$ is now centred around 30 °N. The normal anomaly crests of f_0F_2 are sharper and more pronounced in the night than at day.

In the midday hours of the *E* months, the ratio $D/Q(f_0F_2)$ is greater than 1.00 between 50 °S dip and 50 °N dip with an indication of a slight trough around the equator. Beyond these dip values, the value of $D/Q(f_0F_2)$ gradually falls off with increasing dip. The appearance of the $D/Q(f_0F_2)$ curve is not very different from the normal f_0F_2 curve. In the night hours, again a prominent peak in $D/Q(f_0F_2)$ is centred around the equator, with a suggestion of a secondary peak around 50 °S dip, although beyond 20° dip N and S, the values of $D/Q\,f_0F_2$ are all negative.

In the midday hours of the *J*-months, there is a region of positive $D/Q(f_0F_2)$ centred around the equator, with a second and stronger peak occurring around 40° dip S. Beyond 30 °N dip and 60 °S dip, $D/Q(f_0F_2)$ falls off below 1.00 with increasing dip. There is no resemblance between the $D/Q(f_0F_2)$ curve and the normal anomaly curve. In the night the equatorial peak in f_0F_2 vanishes, and a vast pe... of $D/Q(f_0F_2)$ forms in almost the whole southe... hemisphere with its centre around 40 °S dip. Ne... tive values of $D/Q(f_0F_2)$ occur throughout the ... hemisphere. Again there is no resemblance to n... normal anomaly curve.

The annual behaviour is the average of the 3 season... and is characterised by $D/Q(f_0F_2)$ values exceedi... 1.00 around 40 °S dip in the day, while the equator... peak gains prominence at night. Several interesti... features are:

1. The normal equatorial anomaly is more pronou... ced in the night than by day, particularly in the ... and *E* months.

2. In the day-time of the *D*-months, there seems t... be decreased ionisation at the equator during distu... bances, with peaks in both hemispheres around 45 ... and 45 °S dip. Classically, disturbances are suppose... to fill up the equatorial anomaly trough.

3. The southern 50° dip peak in the *J*-month... (winter months) is stronger than the correspondin... equatorial peak or the northern 50° dip of the D... months. This again shows a marked enhancemen... of *F*-region electron densities over the South America... zone during disturbed conditions. This feature ma... be connected with the low geomagnetic field intensi... in this zone.

STORM-TIME VARIATION OF f_0F_2 — $D_{st}(f_0F_2)$

The storm-time (i.e. universal time) variation... of f_0F_2 were studied with a view to further understand... ing the *F*-region disturbance behaviour in this zone... The strong storms of the IGY-IGC period wit... $Ap \geqq 50$ have been chosen, and their seasonal... behaviour as well as the annual picture obtained fo... each station.

The method of obtaining $D_{st}f_0F_2$ from the ratio... (storm-time value of f_0F_2/ corresponding media... value of f_0F_2) is the same as described in Reference ...

Figure 7 shows the annual average $D_{st}(f_0F_2)$... variations. In the northern hemisphere the positive... phase of $f_0F_2/\overline{f_0F_2}$ (i.e. the values of $f_0F_2/\overline{f_0F_2}$... greater than 1.00), which occurs at equatorial HUA... (+ 2°) gradually decreases as dip increases. A change-... over occurs at (PAN+PMB+BOG) the region o... + 35° dip where the variation is uncertain; beyon... this a negative phase (i.e. the value of $f_0F_2/\overline{f_0F_2}$ les... than 1.00 takes over. This supports the genera... belief that the effect of magnetic storms is to increas... f_0F_2 at the low-latitude regions, and decrease f_0F_2... at the high latitudes. A region such as PUE (+ 5°)... which is at the *Sq* current focus does not seem to be... affected much by disturbances. In the southern... hemisphere the change-over, from the equatorial... positive phase to the high-latitude negative phase... does not occur at the region of least disturbance...

Vol. 27, fasc. 3, 1971

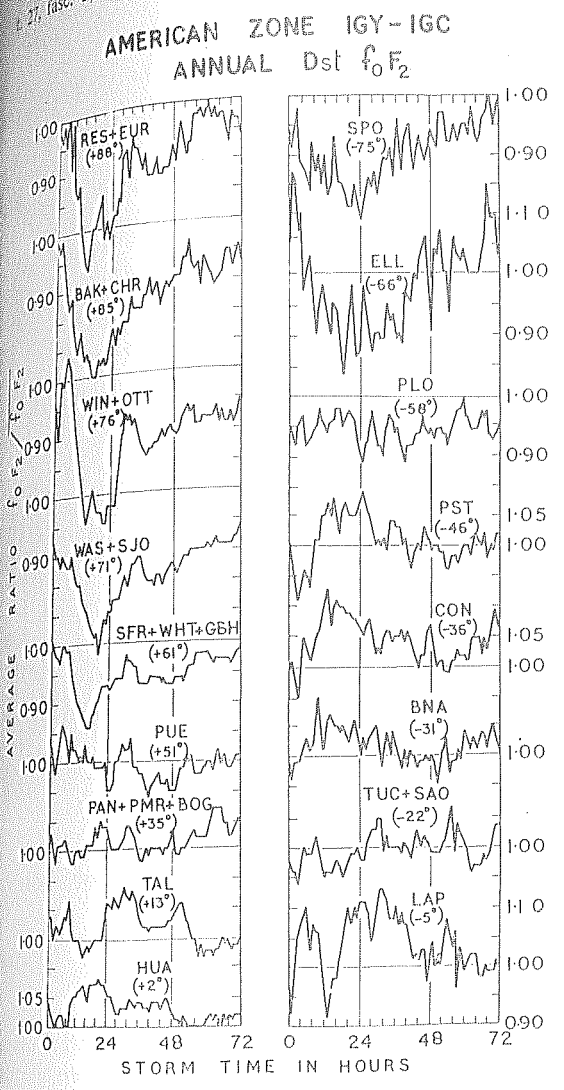


FIG. 7

Annual average D (f_0F_2) variation at different stations during IGY-IGC.

which is around TUC, SAO (— 22°). The positive phase continues lower down till PST (— 46°). Beyond this the negative phase occurs right till SPO (— 75°). PLO (— 58°) shows an unusual variation with almost uniform negative values of $f_0F_2/\overline{f_0F_2}$; there does not seem to be a clearly defined main phase or recovery phase for F_2 disturbances in this region. The 24 hour repetition frequency of the disturbance peaks which was seen in the Asian Zone (Ref. 1) is not prominent in the American zone. The southern high-latitude stations SPO (— 75°) and ELL (— 66°) show very rapid fluctuations of the ratio $f_0F_2/\overline{f_0F_2}$. The maximum F_2 disturbance in higher latitudes, both north and south, seems to occur 20-24 hr after the storm commencement.

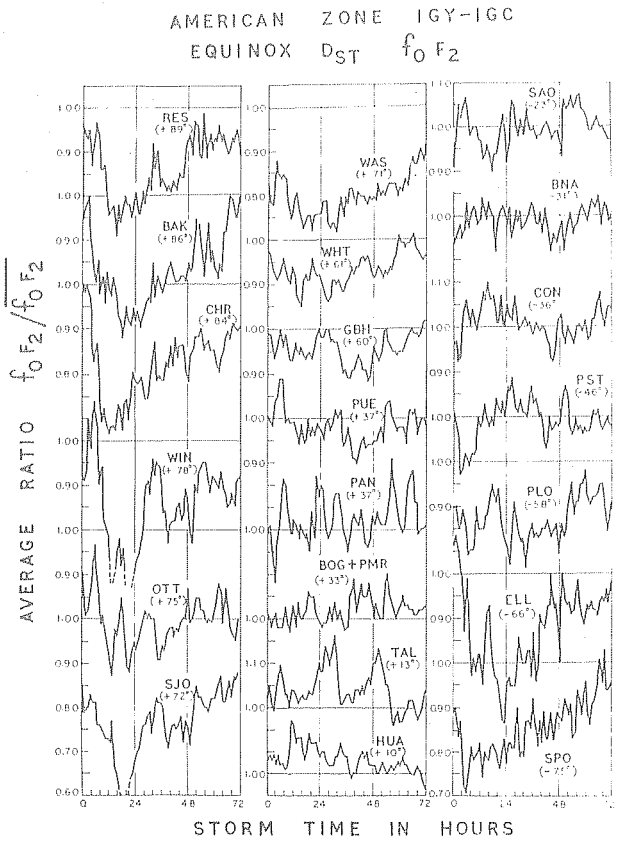


FIG. 8

D_{st} (f_0F_2) variation during equinoxes of IGY-IGC.

The D_{st} f_0F_2 variations during the equinoxes are shown in Figure 8. They do not differ much in character from the annual average behaviour, the regions of change-over being almost the same. The variations at the different stations resemble the annual picture.

In Figure 9 are shown the D_{st} (f_0F_2) variations for the December Solstice which is the northern winter. Here, in the Northern hemisphere the positive phase of D_{st} (f_0F_2) exists from equatorial HUA to WHT (+ 61°). The region of least change in f_0F_2 now seems to have shifted to WAS (+ 71°), and beyond this right till RES (+ 89°), negative variations of f_0F_2 are shown by all stations. In the southern hemisphere negative variations seem to start at the latitude of TUC (— 22°) itself, the decrease in (storm f_0F_2/ median f_0F_2) increasing polewards. The least variation in f_0F_2 is at BNA (— 31°). Pronounced 24-hour peaks are seen in the D_{st} (f_0F_2) variation at WHT (+ 61°) in the north. The northern high latitude stations now show very large and rapid fluctuations of the ratio but these are not seen in the southern high latitude stations; this suggests these fluctuations to be a local winter-time feature.

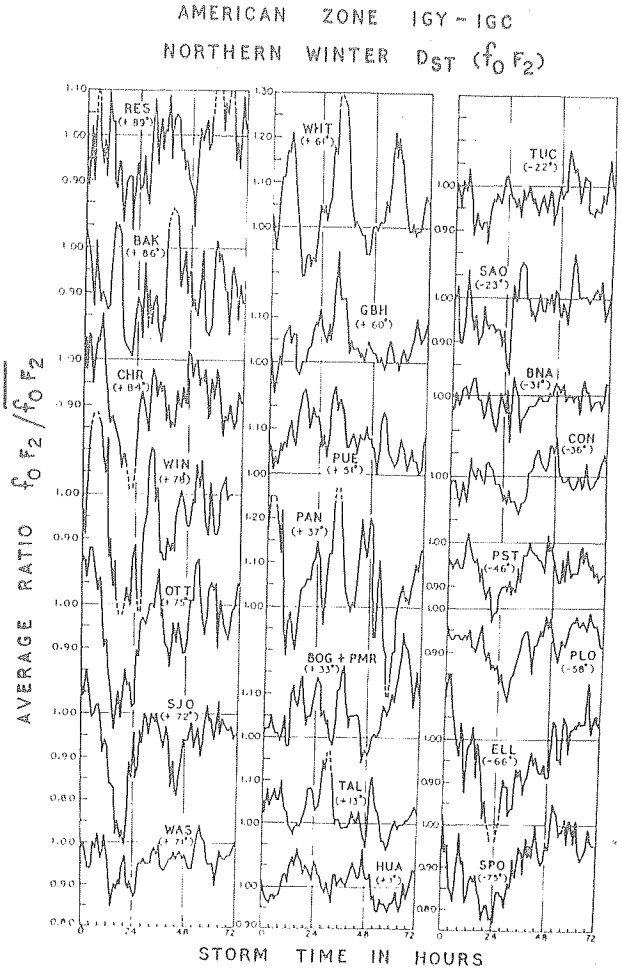


FIG. 9

D_{st} (f_0F_2) variation during December solstices of IGY-IGC.

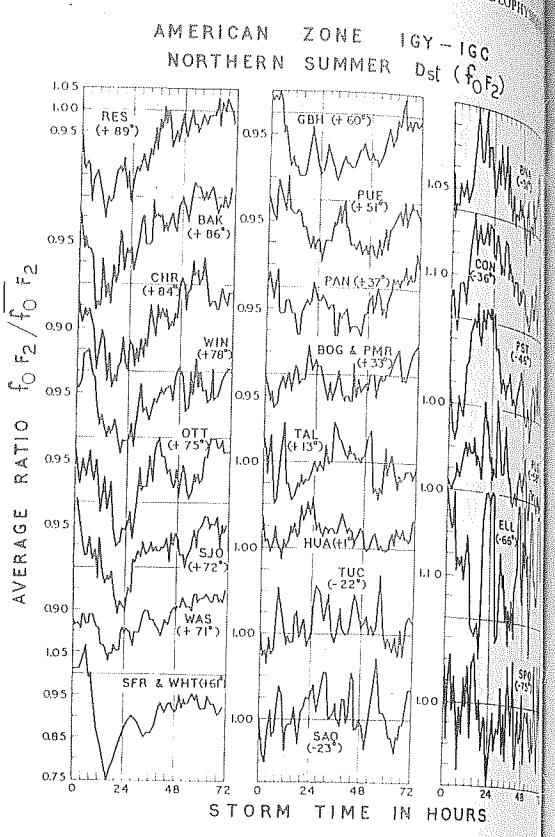


FIG. 10

D_{st} (f_0F_2) variation during June Solstices of IGY-IGC

The D_{st} (f_0F_2) variations for the June Solstice (i.e. northern summer) are shown in Figure 10. Now it is the southern high latitude stations SPO and ELL lying in the winter hemisphere which show large and rapid fluctuations of the ratio $f_0F_2/\overline{f_0F_2}$. The northern high latitude stations, RES, BAK, CHR, WIN, OTT, etc. show comparatively smoother and smaller variations. In this season, in the northern hemisphere, the positive phase of D_{st} (f_0F_2) occurs at the equatorial stations HUA and TAL; the change-over region of little fluctuation occurs at BOG, PMR (+ 33°) and then with increasing dip, the variation becomes more and more negative. In the southern hemisphere, the positive D_{st} (f_0F_2) continues right down till ELL (— 66°), and even at SPO (— 75°) the variation cannot be called a clearly negative one. The 24 hour peaks in D_{st} f_0F_2 are not clearly shown at any of the stations.

CONCLUSIONS

Several deviations from the classical knowledge of f_0F_2 disturbance effects have been brought out in this study. The equatorial decrease of disturbed f_0F_2 in the day-time hours of the IGY-IGC is an unexpected feature and has been dealt with more detail in previous papers [RASTOGI and RAJARAM (1969), RAJARAM and RASTOGI, 1968]. The formation of a peak of disturbed F_2 ionisation in the winter mid-latitudes is a feature of other longitude zones too [RAJARAM and RASTOGI, 1969, 1970]. The physical implications of this are being studied.

ACKNOWLEDGMENT

The authors are grateful to Prof. K. R. Ramanathan for valuable discussions through the course of this study. Thanks are due to Mr. S. S. Pancholi for assistance in the large amount of computational work involved.

Manuscrit reçu le 30 avril 197

vol. 27, fasc. 3, 1971

REFERENCES

Antarctic Research Series, vol. 4, Edited by A. H. Waynick Published by the American Geophysical Union, 1965.

EVANS J. V., "Ionospheric backscatter observations of Millstone Hill," *Planet. Space Sci.*, 13, 1031-1074, 1965.

MATSUSHITA S., "A study of the morphology of ionospheric storms," *J. Geophys. Res.*, 64, 305-321, 1959.

RASTOGI R. G., "The effect of geomagnetic activity on the F_2 region over Central Africa," *J. Geophys. Res.*, 67, 1367-1374, 1962.

RASTOGI R. G. and RAJARAM G., "Abnormal behaviour of f_0F_2 at Huancayo in magnetically active periods of IGY-IGC," *J. Atmos. Terr. Phys.*, 27, 1097-1103, 1965.

RAJARAM G. and RASTOGI R. G., "A synoptic study of the disturbed ionosphere during IGY-IGC (I) the Asian Zone," *Annales de Geophys.*, 25, 795-805, 1969. (Ref. 1)

RAJARAM G. and RASTOGI R. G., "Abnormal electron density distributions over Huancayo on disturbed days of IGY-IGC," *Annales de Geophys.*, 24, 1045-1051, 1968.

RASTOGI R. G., "Abnormal features of the F_2 region of the ionosphere at some southern high-latitude stations," *J. Geophys. Res.*, 65, 585-592, 1960.

RAJARAM G. and RASTOGI R. G., "*F*-region disturbances in the Australasian zone during IGY-IGC," *Ind. Jour. Pure and Applied Phys.*, 8, 551-554, 1970.

THOMAS J. O., "Electron density distributions in the Ionosphere and Exosphere," *Proc. NATO Advanced Study Instit. Norway*, April 1963, (North-Holland Publishing Co, Amsterdam), 226, 1964.

On the pattern of the work published in the attached papers, the analysis was extended to cover the East Zone for the low sunspot years. In the sections which follow, a summary of these results has been made for some selected stations, namely those near the magnetic equator, the sub-tropical peak, at mid-latitudes, and the polar latitudes. Longitudinal differences are studied by comparing the West and East zones for high sunspot (IGY-IGC). The solar cycle effects are seen by comparing the East zone for high sunspot (IGY-IGC) and low sunspot (IQSY + 1953-1955).

The solar daily variations of f_oF_2 at these stations on International Quiet Days (Q) and International Disturbed Days (D) of the different seasons are shown in Fig. 4.10. (Pg. 95 (a)).

The abscissa is the local time in hours while the ordinate is f_oF_2 in MHz. f_oF_2 variations on quiet days are shown by full lines while the variations on Disturbed days are shown by dashed lines.

In any one zone it is generally clear that -

(1) The annual behaviour and E-month behaviour is rather alike. This happens at the equatorial and high-latitude stations because the change in disturbed f_oF_2 during equinox, summer and winter is in the same sense and additive; at high

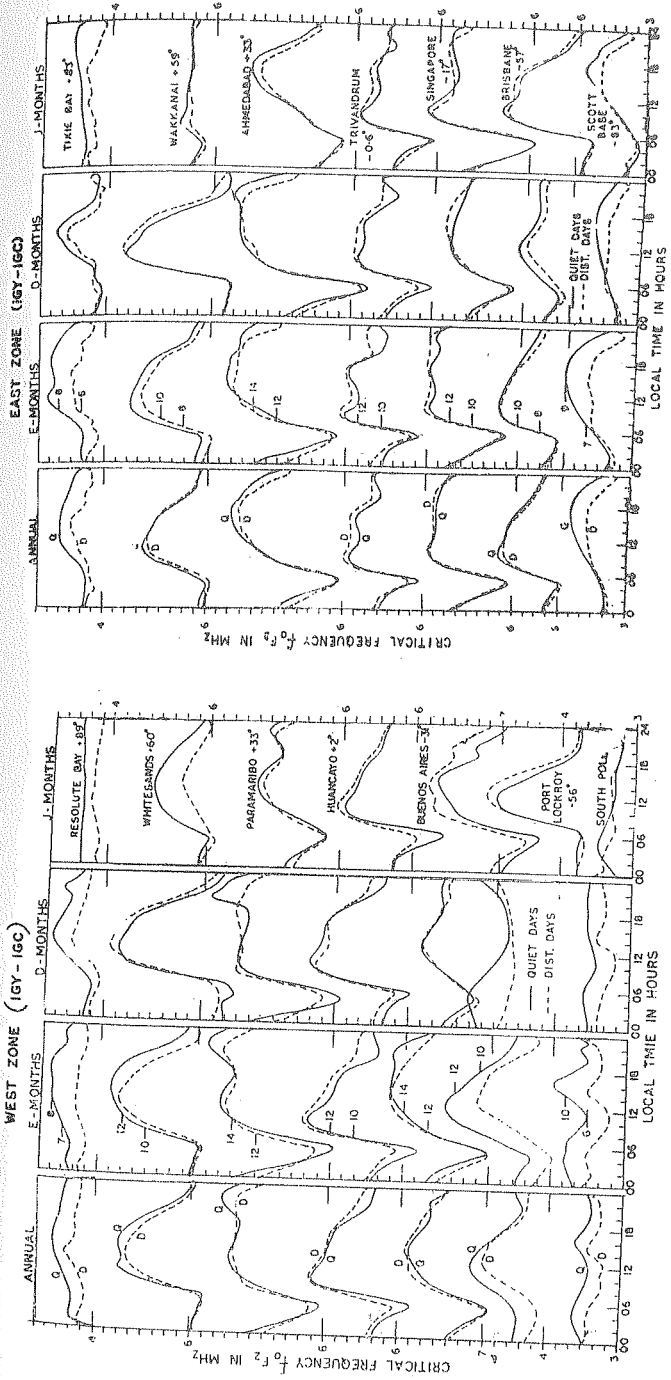
latitudes, it is always a decrease of f_oF_2 on D days in all seasons as compared to Q days, while at equatorial stations it is always an increase.

The exceptions to the above are (1) during IGY-IGC, at the equatorial zone of the West zone in the D-months where there is a decrease of midday (f_oF_2) on D days; this is not seen in the East zone. (2) The northern high latitudes of the East zone in the low sunspot years, when a decrease of f_oF_2 on D-days occurs only in the J-months (local summer), but the D-months, E-months and Annual average all show f_oF_2 on D days almost equal to Q days. This is unlike the East zone (high sunspot).

Low and mid-latitude stations show opposite behaviour between local summer and winter, but the magnitude of changes being equal and opposite, they annul out, and render the Annual variation similar to the equinoctial variation.

(2) There is a post-sunset rise in f_oF_2 at the dip locations of about 33° north and south (more in the north than in the south) in the high sunspot years in both East and West zones (Evans 1965 b). This rise is certainly less on D days than on Q days. (Huang Y.N.1964; Huang Y.N. and C.Y. Leh 1970).

(3) The high-latitude stations both north and south show a sharper daily variation of f_oF_2 in local winter when


WEST ZONE (IGY-IGC)
E-MONTHS
D-MONTHS
J-MONTHS
ANNUAL
RESOLUTE BAY +83°
WHITEGANDS -60°
PARAMARIBO +33°
HUANCAYO +2°
BUENOS AIRES -36°
PORT LOCKROY -56°
SOUTH POLE
QUIET DAYS
DIST. DAYS
CRITICAL FREQUENCY f_0F_2 IN MHz
LOCAL TIME IN HOURS

EAST ZONE (IGY-IGC)
E-MONTHS
D-MONTHS
J-MONTHS
ANNUAL
TIKIE BAY +83°
WAKKANAI +59°
AHMEDABAD +33°
TRIVANDRUM -0.6°
SINGAPORE -12°
BRISBANE -57°
SCOTT BASE -83°
QUIET Days
DIST. DAYS
CRITICAL FREQUENCY f_0F_2 IN MHz
LOCAL TIME IN HOURS

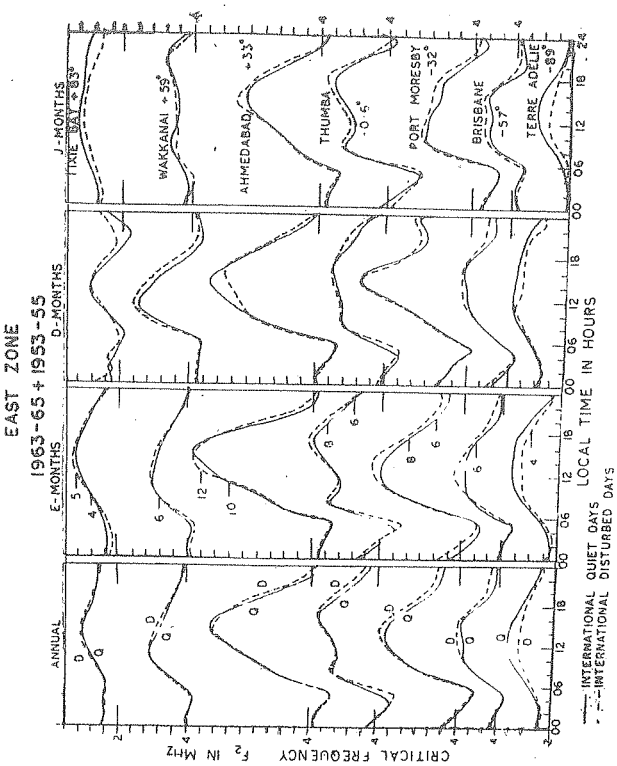

EAST ZONE
1963-65 + 1953-55
E-MONTHS
D-MONTHS
J-MONTHS
ANNUAL
TIKIE BAY +83°
WAKKANAI +59°
AHMEDABAD +33°
THUMBA -0.5°
PORT MORESBY -32°
BRISBANE -57°
TERRE ADELIE -89°
CRITICAL FREQUENCY f_2 IN MHz
LOCAL TIME IN HOURS
INTERNATIONAL QUIET DAYS
INTERNATIONAL DISTURBED DAYS

Fig. 4.10

ionising solar radiation is totally absent, and an almost flat daily variation of f_oF_2 in local summer when solar ionising radiation is present. This suggests that F_2 ionisation at these latitudes is primarily governed by transport effects (from the magnetosphere or from other latitudes) rather than by processes connected with solar electromagnetic radiation alone (Rastogi 1960; Antarctic Research Series 1965). The anomalous variation of f_oF_2 at Port Lockroy (- 56° dip) in the West zone, with night f_oF_2 larger than daytime f_oF_2 may be noted. It has been pointed out that this feature is due to the ionospheric drift produced by atmospheric wind systems (King J.W. et al., 1967). This anomalous variation is considerably less on D days, the difference in f_oF_2 between day and night being less as compared to Q days. It looks as though magnetic disturbances have a tendency to smoothen out this F_2-region Antarctic anomaly.

(a) Solar cycle differences

Comparing the S_q, S_d' curves for different sunspot periods it appears that:

(1) The absolute difference in MHz between f_oF_2 on D days and Q days in low sunspot years is less than in high sunspot years; percentage-wise this difference is as much if not more in low sunspot years, as will be

shown in Section 5.4 .

(2) The post-sunset rise in f_oF_2 seen at Ahmedabad (+ 33° dip) in high sunspot is absent in low sunspot. It should be noted that the post-sunset height rise of the F_2 layer at equatorial stations is also absent in low sunspot years. This establishes a relationship between the two features. The dependence of the post-sunset rise in f_oF_2 at a mid-latitude station on the post-sunset rise in h'F at an equatorial station has been studied for quiet conditions by Narasinga Rao (1966).

While Ahmedabad experiences decreased f_oF_2 in all seasons on D days in high sunspot, this is seen only in the D-months in low sunspot. In fact, E-months and J-months both show increased f_oF_2 on D days at Ahmedabad. In low sunspot years, all latitudes except the highest southern latitudes experience increase in f_oF_2 during D days. This goes against the classical belief of storm-time behaviour. In high sunspot years, this range of latitudes experiencing f_oF_2 increase on D-days in considerably reduced.

(3) At equatorial stations (Trivandrum −0.6° dip) in high sunspot years, the forenoon peak in midday f_oF_2 is stronger than the afternoon peak; in low sunspot years the afternoon peak is higher than the forenoon peak (Rastogi and Sanatani 1963).

(4) In the northern hemisphere of the East zone, in both high and low sunspot periods, Wakkanai (+ 59° dip) seems to experience its peak f_oF_2 before midday, while Ahmedabad (+ 33° dip) lying south of it, and Tixie Bay (+ 83° dip) lying north of it, both experience peak f_oF_2 after 12 hr. This suggests that some agent responsible (may be partly) for peak ionisation at 59° dip travels both north and south, taking about 3 hr. to influence locations at + 83° dip and + 33° dip .

(5) In the J-months, the f_oF_2 variation at Wakkanai (+ 59°) is remarkably flat on both Q and D days. This is true for both high and low sunspot.

(6) At high latitudes, the local winter feature of sharper f_oF_2 variation, and a flat summer variation persists in both high and low sunspot years. It is equally true of Q and D days.

(b) Longitudinal differences

Comparing the East and West zone for high sunspot, we find:

(1) The extremely flat variation of f_oF_2 at Wakkanai (+59° dip East zone) in the J-months is not found at Whitesands (+60° dip, West zone). The difference between D (f_oF_2) and Q (f_oF_2) is much larger at the latter station. However the variation of f_oF_2 in the D-months is

extremely similar at the two stations; the similarity is seen even in D (f_oF_2) being greater than Q(f_oF_2) only from noon onwards.

(2) The post-sunset rise in f_oF_2 at + 33° dip in the West zone is much larger than in the East zone. It is interesting to see that this post-sunset rise in f_oF_2 is less on D days than on Q days in both zones and both hemispheres.

(3) The abnormal decrease of D (f_oF_2) in D-months at equatorial Huancayo (+ 2° dip) in the West zone is not seen at equatorial Trivandrum (- 0.6° dip) in the East zone. Also the midday bite-out in f_oF_2 seen at Trivandrum is absent at Huancayo; at the latter it is observed on the disturbed days of the D-months.

(4) The difference between D (f_oF_2) and Q (f_oF_2) at southern mid and high latitudes is much greater in the West zone than in the East zone. Also the anomalous feature of night f_oF_2 exceeding daytime f_oF_2 in D-months seen at -56° dip (Port Lockroy) in the West zone is not seen at the corresponding dip (Brisbane) in the East zone.

Paper 6

Journal of Atmospheric and Terrestrial Physics, 1965, Vol. 27, pp. 1097–1103. Pergamon Press Ltd. Printed in Northern Ireland

SHORT PAPER

Abnormal behaviour of f_0F2 at Huancayo in magnetically active periods of IGY-IGC

R. G. Rastogi and G. Rajaram
Physical Research Laboratory, Ahmedabad-9, India

(*Received* 8 *September* 1964)

Abstract—The way in which f_0F2 near noon varies with magnetic activity at different epochs of solar activity is studied. In the American zone, the normal equatorial increase in noon f_0F2 for disturbed days is replaced by a decrease in f_0F2 during the December solstice (local summer) of years with large solar and magnetic activity.

Appleton *et al.* (1937) had found a strong negative correlation between the critical frequency of the $F2$-layer (f_0F2) and the magnetic activity at high latitude stations, Slough and Tromso. Berkner and Seaton (1940) showed that the electron density averaged for the whole day at equatorial station, Huancayo, increased continuously with the increase of magnetic activity during any of the seasons. Whereas, at temperate latitude station Watheroo, the electron density during summer months decreased continuously with the increase of magnetic activity but during the winter months it increased for small magnetic activities and then decreased as the activity became more severe.

Appelton and Piggott (1955) found that the ratio of noon f_0F2 during disturbed and quiet days of the equinoxes at various ionospheric stations of the world when plotted against geomagnetic latitude, showed negative phase at both northern and southern high latitudes and a positive phase over a belt at the magnetic equator. Skinner and Wright (1955) found that the mean value of the maximum electron density of the $F2$-layer between 1000 and 1400 hours at Ibadan showed monotonic increase with the daily sum of magnetic K_p index. Rastogi (1962) showed that the mean value of $(f_0F2)^2$ for 11, 12 and 13 hr at equatorial stations Ibadan, Huancayo and Djibouti increased with increasing daily sum of K_p index during the June as well as December solstices. On the other hand, at temperate latitude stations Lwiro, Leopoldville and Tananarive the increasing K_p index increased mean $(f_0F2)^2$ during local winter months but decreased it during local summer months.

Obayashi (1952) found that the daily variation on magnetically disturbed minus that on quiet days, called disturbance daily (SD) variation of the $F2$-layer at Wakkanai consisted of an increase of the virtual height and the decrease of the critical frequency of the $F2$-layer, the effect being much more pronounced in summer than in winter months. Comparing SD(f_0F2) variation at a number of stations, Martyn (1953a) found that there is a general tendency for the electron density to be lowered on the average at high latitudes and raised at low latitudes. The SD (f_0F2) variation at Huancayo was positive for any time of the day. In a later paper Martyn (1953b) studied SD(f_0F2) variation at temperate latitude stations Washington, Canberra and Watheroo and found that the mean values of f_0F2 were depressed in summer and equinoxes but the effect was very much smaller in winter; actually f_0F2 was slightly raised for Canberra and Watheroo. Matsushita (1955) studied SD(f_0F2) variation at Huancayo from January 1951 to July 1952 and found that the variation was not too clear, a maximum seemed to occur at dawn and the maximum for harmonic results occurred in the daytime. Skinner and Wright (1955) found that the effect of magnetic activity at Ibadan consisted of an increase of f_0F2 at all hours of the day with a corresponding lowering of the height of the layer. Rastogi (1962) studied SD(f_0F2) variation at stations in Central African regions and showed that the values of

f_0F2 at Ibadan, Djibouti and Huancayo were generally higher during the disturbed than the quiet days of the June as well as the December solstices whereas at Lwiro, Leopoldville and Tananarive the disturbed day values were greater than the quiet day values during the June solstice (local winter) and smaller during the December solstice (local summer). It was concluded that the magnetic disturbance generally increases the f_0F2 at low dip latitude (not geomagnetic latitude) stations during any of the seasons while at temperate latitudes the disturbance produces a decrease during local summer and an increase during local winter months.

Rastogi (1964) showed that the lunar perturbations in f_0F2 and in the horizontal component of earth's magnetic field, H, at equatorial stations are closely related being almost opposite in phase to each other. It was attempted to study if there exists similar relations between the

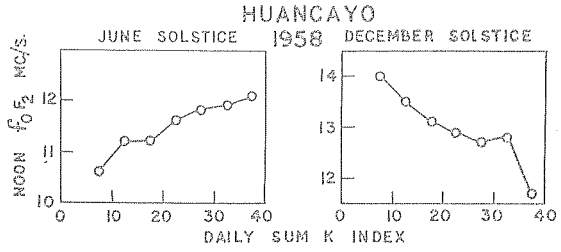


Fig. 1. The relation between the noon value of f_0F2 and the daily sum of the K index at Huancayo for the June and December solstices of the year 1958.

perturbations of f_0F2 and H caused by magnetic disturbances. Contrary to the expectations, the variations in f_0F2 and H at Huancayo were found to be very similar to each other during certain periods of IGY and IGC. A detailed study of the simultaneous variations in f_0F2 and H at Huancayo during magnetically active periods was therefore undertaken.

To examine the relation of noon value of f_0F2 and the degree of geomagnetic activity at Huancayo during the maximum sunspot year of 1958, the days are divided into groups with the daily sum of Huancayo magnetic index, K figure being between 0–4, 5–9, 10–14, 15–19, 20–24, 25–29, 30–34 and 35–39. The average value of f_0F2 at noon for each group of days so formed is computed separately for the June solstice (May, June, July and August months) and for the December solstice (November, December, January and February months). Figure 1 shows the relation between noon f_0F2 and the daily sum K index for the two seasons. During June solstice (local winter), one finds the monotonic increase of f_0F2 with K index. But during December solstice (local summer), f_0F2 decreases monotonously with increasing K index. Rastogi (1962) has shown that the mean mid-day value of f_0F2 at Huancayo and other equatorial stations for the low sunspot period (1952–1953) increased with increasing interplanetary K_p index during either of the solstices. Thus the effect of geomagnetic activity in noon f_0F2 at Huancayo during local summer months is opposite during the low and high sunspot years.

To further elucidate the effect of magnetic activity on f_0F2, the average solar daily variation of f_0F2 and H at Huancayo are computed for the International Five Quiet (Q) and Five Disturbed (D) days of the two solstices of IGY and IGC and are shown in Fig. 2. The disturbance daily (SD) variations of f_0F2 and H are also shown in the Fig 2.

During June solstice (local winter) the value of f_0F2 at Huancayo is greater on disturbed than on quiet days for any hour of the day. The SD(f_0F2) variation is positive for any hour of the day, shows slightly higher values during the forenoon than the afternoon hours and a peak at about dawn period. During December solstice (local summer), f_0F2 is greater on disturbed than on quiet days for the night time hours only; but the values between about 0800 and 1600 hours are lower on disturbed than on quiet days. The SD(f_0F2) variation is strongly diurnal in character with a minimum around mid-day hours.

Regarding the horizontal component of earth's magnetic field, H, its value for any hour of the day and for either of the solstices is markedly lower on disturbed than on quiet days,

i.e. the SD(H) variation is negative for any of the hours. There is no significant difference in SD(H) variation in the two solstices, except that the effect is comparatively larger during June solstice.

To find out the latitudinal extent of this abnormal behaviour of SD(f_0F2) variation during the December solstice, the average daily variations of f_0F2 are computed for the quiet and disturbed days of the two solstices of 1958 at all stations in the American zone. These curves are shown in Fig. 3.

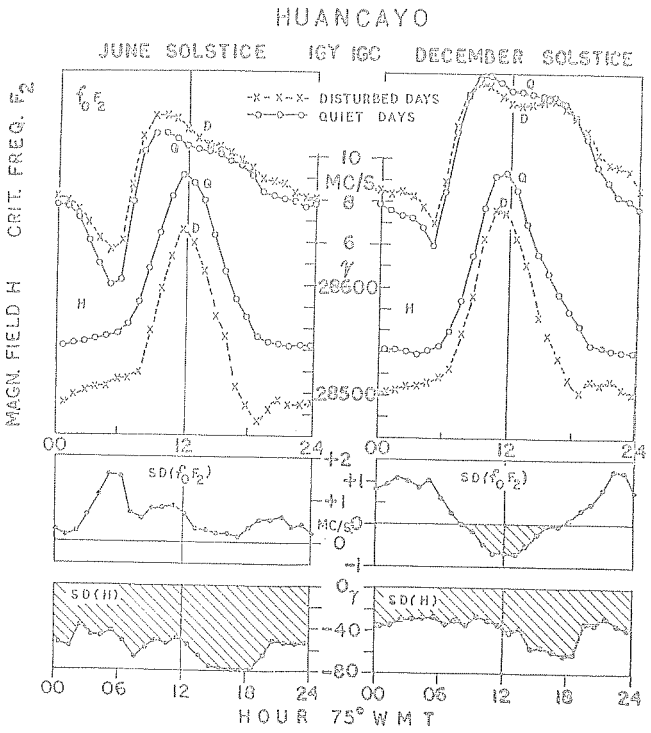


Fig. 2. Average daily variation in magnetically quiet and disturbed days, and the disturbance daily variations of f_0F2 and H at Huancayo during the June and December solstices of IGY and IGC.

During the June solstice, the values of f_0F2 during the daytime hours at the equatorial stations Huancayo, Chimbote, Chiclayo and Talara are greater on disturbed than on quiet days. At Bogota there is little difference between the quiet and disturbed day values of f_0F2 while at temperate latitude station Panama (not shown in the diagram) and Puerto Rico, the value of f_0F2 for any hour is smaller on the disturbed than on quiet days. This decrease of f_0F2 due to magnetic disturbance, is much larger at high latitude station, Washington. The SD(f_0F2) variation at southern latitude station Sao Paulo is very small during the daytime hours. At Buenos Aires and Port Stanley the value of f_0F2 is greater on disturbed than on quiet days. At Port Lockroy (not shown in the diagram), the SD(f_0F2) was similar to that at Port Stanley. It is interesting to note that in spite of high geographic latitude of Port Lockroy (65° S), the SD(f_0F2) variation at this station is similar to that at southern temperate latitude stations Leopoldville and Lwiro (Rastogi, 1962) and opposite to that at northern temperate latitude stations Panama and Puerto Rico.

During the December solstice, the value of f_0F2 between 0800 and 1600 hours at any of the equatorial stations Huancayo, Chimbote, Chiclayo and Talara is markedly smaller on disturbed

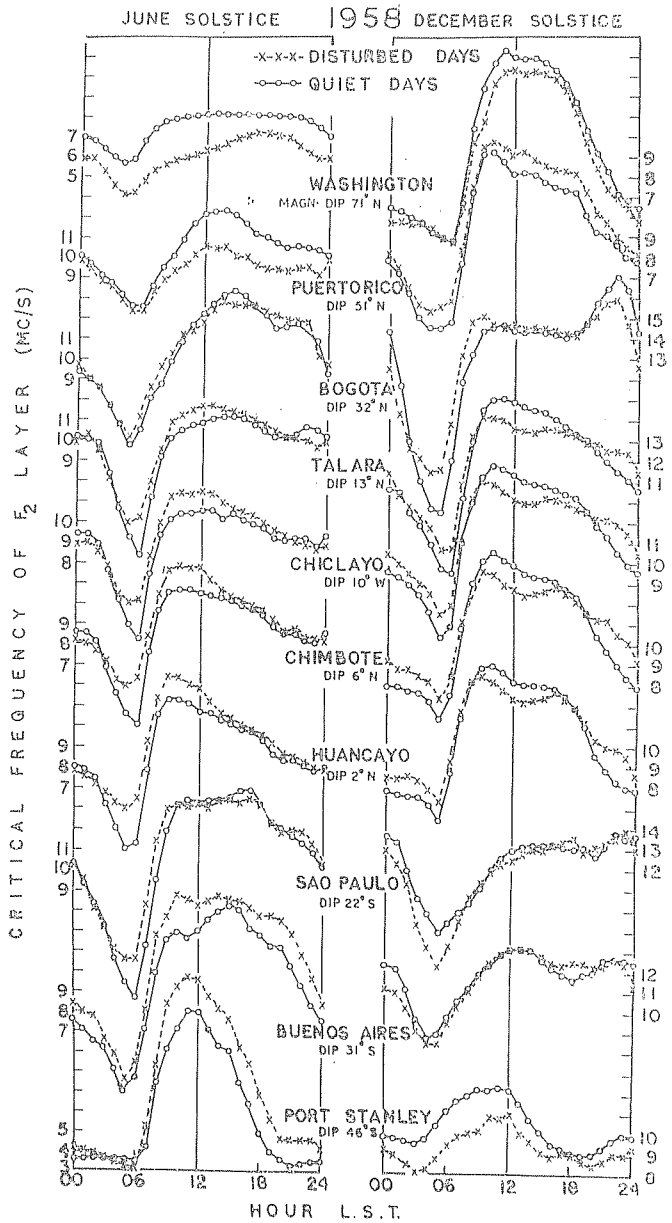


Fig. 3. Average daily variations of f_0F2 on international quiet and disturbed days of June and December solstices of 1958 at the various stations in the American zone.

than on quiet days. At Bogota, the daytime f_0F2 is slightly greater on disturbed than on quiet days while at Panama and Puerto Rico the increase of f_0F2 on disturbed days is quite large and distinct. At Washington disturbed day values are smaller than the quiet day values. At southern stations Sao Paulo and Buenos Aires, there is very little difference between f_0F2 on quiet and disturbed days. At Port Stanley, f_0F2 for any hour is significantly smaller on disturbed than on quiet days. Thus excepting Panama and Puerto Rico all other stations in the American zone show a decrease of f_0F2 due to magnetic disturbance during the December solstice of 1958.

Comparing the daily variations of f_0F2 at local summer and winter months, it is seen that Washington behaves like a high latitude station experiencing decreased f_0F2 on disturbed days at both the solstices. Puerto Rico, Panama and Port Stanley behave as a temperate latitude station, magnetic disturbances causing an increase of f_0F2 during local winter and decrease of

Table 1. The mid-day (1100, 1200, 1300 hour mean) value of f_0F2 at Huancayo averaged for five international quiet (Q) and disturbed (D) days of the June and December solstices of various years

	June solstices				December solstices		
Year	$D(f_0F2)$ (Mc/s)	$Q(f_0F2)$ (Mc/s)	Ratio $\left(\frac{D(f_0F2)}{Q(f_0F2)}\right)$	Year	$D(f_0F2)$ (Mc/s)	$Q(f_0F2)$ (Mc/s)	Ratio $\left(\frac{D(f_0F2)}{Q(f_0F2)}\right)$
1953	6·20	6·00	1·03	1953–54	10·87	10·23	1·06
1954	5·87	5·60	1·05	1954–55	11·10	10·53	1·05
1955	7·16	6·33	1·13	1955–56	14·47	14·30	1·01
1956	11·12	10·13	1·10	1956–57	17·73	17·23	1·03
1957	11·56	10·39	1·11	1957–58	16·87	17·44	0·97
1958	11·29	10·28	1·10	1958–59	17·33	18·40	0·94
1959	11·24	10·96	1·03	1959–60	16·70	17·33	0·96
1960	10·58	9·78	1·08	1960–61	14·50	14·57	1·00
1961	7·89	6·83	1·16	(Nov–Dec) 1961	10·95	9·85	1·11

f_0F2 during local summer months. The abnormality exists in the behaviour of f_0F2 at equatorial stations Huancayo, Chimbote, Chiclayo and Talara where the magnetic disturbance causes an increase of daytime f_0F2 during local winter and decrease of the same during local summer months in the same way as at any temperate latitude station.

To find out the extent of the years during which the decrease of daytime value of f_0F2 at Huancayo during disturbed periods are found, the mid-day (1100, 1200 and 1300 hour mean) value of f_0F2 at Huancayo averaged for the quiet and disturbed days of the June and December solstices of the years 1953–1961 are collected in Table 1. The ratio of f_0F2 on D and Q days for each solstice is also given. During the June solstices of any of the years the mid-day f_0F2 value is greater on disturbed than on quiet days. The ratio $D(f_0F2)/Q(f_0F2)$ ranges between 1·03 and 1·16. During the December solstices f_0F2 is greater on disturbed than on the quiet days for the years 1953–1954 to 1956–1957, the ratio $D(f_0F2)/Q(f_0F2)$ being only between 1·01 and 1·06. During the December solstices of 1957–1958 to 1960–1961 the f_0F2 is smaller on disturbed than on quiet days, the ratio $D(f_0F2)/Q(f_0F2)$ being between 0·94 and 1·00. During the November–December months of 1961 the f_0F2 is again larger on disturbed than on quiet days.

To find out the $SD(f_0F2)$ variation at different stages of solar activity, the average daily variations of f_0F2 on disturbed and quiet days of each of the June and December solstices between the years 1953 and 1961 are shown in Fig. 4.

During the June solstice of any of the years 1953–1961, the value of f_0F2 is greater on the disturbed than on the quiet days for almost any hour of the day or night. The difference in f_0F2 on D and Q days is small for the years 1953 and 1954 but quite large for the years 1957 and 1958.

During the December solstice, f_0F2 is larger on disturbed than on quiet days for almost all hours of the day in the years 1953–1954 and 1954–1955. In the season 1955–1956 few of the afternoon values of f_0F2 tend to be smaller on disturbed days, while the forenoon values are still larger on disturbed than on quiet days. In the season 1956–1957 the values of f_0F2 between 1500 and 1900 hours are decreased on disturbed days. The depression of the values of f_0F2 on disturbed days is found to be during 1000–1600 hours in 1957–1958. This depression of mid-day value of f_0F2 is very pronounced in 1958–1959 and 1959–1960, but the effect is very much

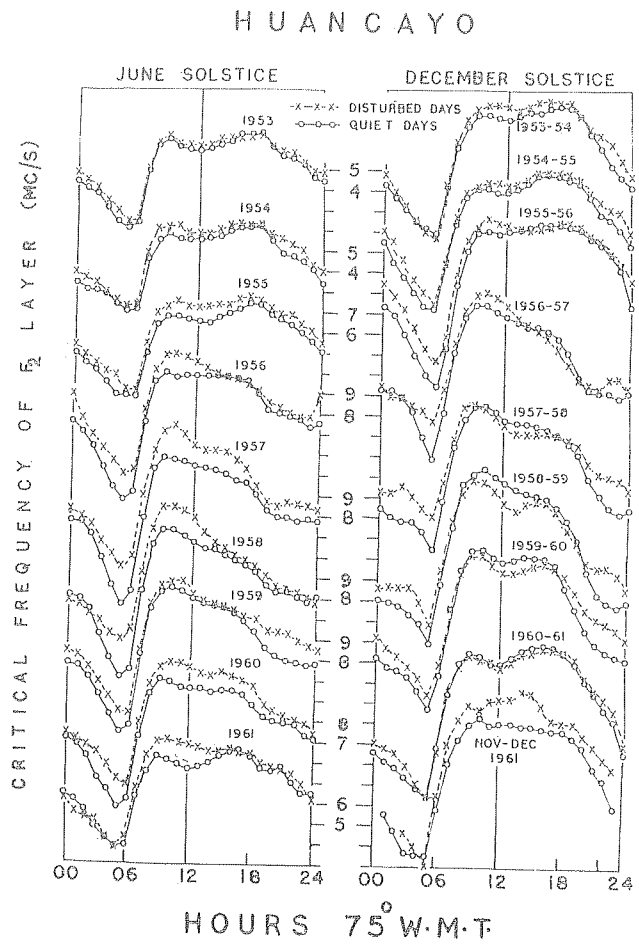


Fig. 4. Average daily variations of f_0F2 at Huancayo on international quiet and disturbed days of June and December solstices of the years 1953–1961.

reduced in 1960–1961. During the months of November–December 1961, SD variation seems to have been reversed, the values of f_0F2 are significantly larger on disturbed than on quiet days. Thus within the period of 1953–1961 studied at present the abnormal SD(f_0F2) variation at Huancayo is found during the December solstices of the years 1957–1958 to 1959–1960 and to a smaller extent in 1960–1961, i.e. during the period of maximum solar activity.

To find out the longitudinal extent of the anomalous behaviour of f_0F2 on disturbed days, the solar daily variations of f_0F2 on quiet and disturbed days of 1958 are computed for other equatorial stations, Ibadan and Kodaikanal. These curves are compared with those for Huancayo in Fig. 5. It is seen that the daytime values of f_0F2 at Ibadan and Kodaikanal are

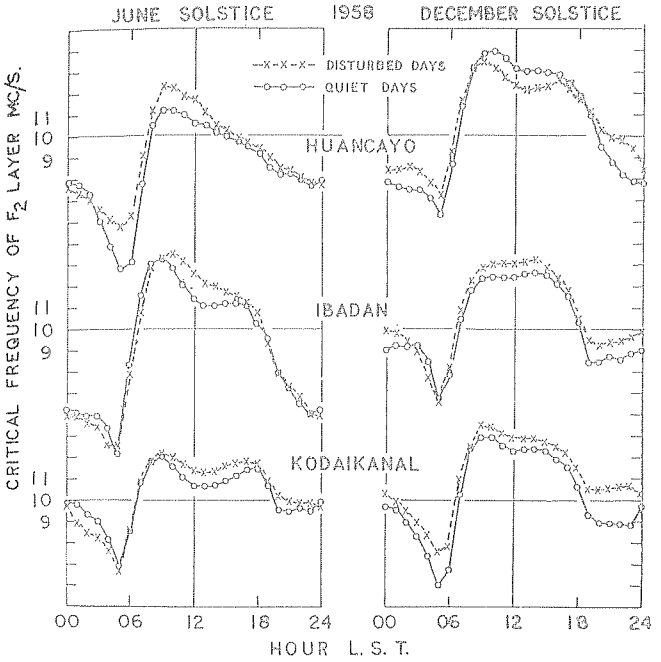


Fig. 5. Solar daily variations of f_0F2 on international disturbed and quiet days of the June and December solstices of 1958 at the equatorial stations Huancayo, Ibadan and Kodaikanal.

greater on disturbed than on quiet days of either of the seasons and are thus similar to the results for the low sunspot years. It is only at Huancayo during the December solstice when the values of f_0F2 are decreased during the daytime on magnetically disturbed days. Thus the anomaly seems to be restricted to the equatorial stations in the American zone during the maximum sunspot years 1957–1958.

Acknowledgements—The authors are thankful to Dr A. A. Giesecke and to World Data Centre A for Ionosphere and Airglow, Boulder for supplying the data of Huancayo. Thanks are also due to Prof. K. R. Ramanathan for stimulating discussions and to Mr. M. C. Sharma and Mrs. S. P. Jani for assistance in the preparation of the paper.

References

Appleton E. V., Naismith R. and Ingram L. J.	1937	*Phil. Trans. Roy. Soc.* **A236**, 191.
Appleton E. V. and Piggott W. R.	1955	*Physics of the Ionosphere*, p. 219. The Physical Society, London.
Berkner L. V. and Seaton S. L.	1940	*Terr. Magn. Atmos. Elect.* **45**, 419.
Martyn D. F.	1953	*Nature, Lond.* **171**, 14.
Matsushita S.	1955	*Physics of the Ionosphere*, p. 265. The Physical Society, London.
Obayashi T.	1952	*Rep. Iono. Res., Japan* **6**, 79.
Rastogi R. G.	1962	*J. Geophys. Res.* **67**, 1367.
Rastogi R. G.	1964	*Z. Geophys.* In press.
Skinner N. J. and Wright R. W.	1955	*J. Atmosph. Terr. Phys.* **6**, 177.

Ann. Géophys., t. 24, fasc. 4, 1968, p. 1045 à 1051.

Paper 7

Abnormal electron density distributions over Huancayo on disturbed days of IGY/IGC

by Girija RAJARAM and R. G. RASTOGI,
Physical Research Laboratory, Ahmedabad-9, India.

RÉSUMÉ. — *L'étude de la valeur à midi de f_0F2 à Huancayo pendant les années 1938 à 1962 montre que f_0F2 est plus élevé pendant les jours perturbés (D) que pendant les jours calmes (Q) ; on l'observe pour les deux solstices sauf pendant les solstices de décembre 1957 et 1960. Le rapport des valeurs à midi de f_0F2 pendant les jours D et Q varie en fonction inverse du nombre de taches solaires pendant les solstices de décembre. Les profils Nh à Huancayo, Puerto-Rico et Fort Monmouth pendant les jours D et Q indiquent que les variations se produisent généralement au-dessus du niveau 200 km ; la densité électronique est accrue à Huancayo et diminuée à Fort Monmouth pour l'une et l'autre saison cependant qu'à Puerto Rico, la densité électronique augmente pendant l'hiver et décroît pendant les mois d'été de 1961. La variation journalière de la perturbation au cours de 1961 montre que les principaux changements se produisent au voisinage des heures méridiennes. Pendant les mois de novembre de 1957 et 1958 à Huancayo et Chimbote, la densité électronique pour toutes les altitudes supérieures à 300 km était plus faible pendant les jours perturbés que pendant les jours calmes alors que pendant les mois de juillet des mêmes années, la densité électronique était supérieure pendant les jours perturbés. Les variations de f_0F2 avec Dst pendant chacune des saisons des années d'activité solaire faible aussi bien que d'activité solaire forte sont de type positif, f_0F2 étant plus élevé pendant les jours d'orage que pendant les jours normaux. Les variations Dst semblent plus accusées pendant les années de faible activité solaire et se poursuivent sur une période plus longue que pendant les années de forte activité solaire indiquant une sorte d'effet de saturation sur l'ionosphère équatoriale durant les années de forte activité solaire.*

ABSTRACT. — *Studying the midday value of f_0F_2 at Huancayo during 1938 to 1962, it has been found that f_0F_2 is higher on disturbed (D) than on (Q) quiet days during either of the solstices, except during the December solstices of 1957 to 1960. The ratio of midday f_0F_2 on D and Q days shows inverse relationship with sunspot number during December solstices. The N-h profiles at Huancayo, Puerto Rico and Fort Monmouth during D and Q days indicate that the changes occur generally above the level of 200 km; the electron density is increased at Huancayo and decreased at Fort Monmouth, for either of the seasons, while at Puerto Rico, the electron density increases during winter, and decreases during summer months of 1961. Disturbance daily variation during 1961 shows that the major changes occurred around the midday hours. During November months of 1957-58 at Huancayo and Chimbote, the electron density at any height above 300 km was lower on disturbed than on quiet days, while during July months the electron density was higher on D than on Q days. The D_{st} variations of f_0F_2 in any of the seasons of low, as well as high sunspot years, show a positive type of variation, f_0F_2 on storm days being higher than normal. The D_{st} variation seems to be more prominent during the low sunspot years, and continues for a longer period than during high sunspot years, indicating some kind of saturation effect on the equatorial ionosphere during high sunspot years.*

INTRODUCTION

It has been long known that magnetic disturbances decrease the critical frequency of the F_2 layer (f_0F_2) at high latitudes [APPLETON and INGRAM, 1935 ; HARANG, 1937 ; APPLETON, NAISMITH and INGRAM, 1937 ; APPLETON and PIGGOTT, 1950]. At the equatorial stations, it was found that the magnetic storms had an opposite effect, the critical frequency being increased during any of the seasons [BERKNER and SEATON, 1940 ; SKINNER and WRIGHT, 1955 ; MARTYN, 1953]. At medium latitudes the effect of the magnetic storms on f_0F_2 had pronounced dependence on the season. MARTYN [1953b] showed that f_0F_2 at Watheroo dropped steadily with the increase of the magnetic character figure during summer months, while during winter months it first increased with magnetic activity, and tended to decrease during the periods of intense magnetic disturbance. MATSUSHITA [1959] studied the ionospheric storms at a large number of stations and concluded that the D_{st} variation at high latitudes is characterized by a short increase followed by much larger decrease, the amplitude of decrease being accentuated in summer. In the equatorial regions, there is an increase after an initial short decrease, with no seasonal effect. At intermediate latitudes, the D_{st} variation resembles that at high latitude during summer, and that at equatorial regions during winter, with the average over all seasons being relatively flat. RASTOGI [1962] showed that the effect of the magnetic storms on f_0F_2 is governed by the dip angle of the station, and not by its geographic or geomagnetic latitude. The effect of magnetic disturbances on the ionosphere was also studied by BHARGAVA and RAO [1959] at Kodaikanal.

While studying the ionospheric storm effects at Huancayo during the IGY and IGC period, it was found [RASTOGI and RAJARAM, 1965] that during the June solsticial months, f_0F_2 increased with the increase of the magnetic activity but during the December solsticial months, the frequency steadily decreased with the increase of K index. The average critical frequency, during any of the daytime hours, was found to be lower during disturbed than on the quiet days of December solsticial months of 1958, at equatorial stations, Talara, Chiclayo, Chimbote and Huancayo. This abnormal effect was present during the years of 1957-60 but not during the years 1953-56. Further, during the year 1958, other equatorial stations like Ibadan and Kodaikanal, did not show any decrease of f_0F_2 during the disturbed days. It was concluded that this abnormal decrease of the critical frequency at the equatorial stations during magnetic storms, was confined only to American regions, and only during December solsticial months of IGY/IGC.

In the present paper we have studied the variations of electron density profile and true parameters of the F_2 layer during conditions of quiet and disturbed days of a year of relative low sunspot i.e. 1961 and a year of maximum sunspot i.e. 1957-58. The electr density profiles have been calculated by the us Budden's matrix methods using the IBM 1620 comp ter, from the ionograms which were kindly suppli by C.R.P.L. (now I.T.S.A.), Boulder, U.S.A.

To find out exactly the periods during which t abnormal behaviour of ionospheric storms wa observed, the ratios of midday critical frequency o Five International Disturbed and Five Internationa Quiet Days were computed for the D-months (Novem ber, December, January and February) and fo J-months (May, June, July and August) for all th years 1938 to 1962. Figure 1 shows the variations o these ratios compared with the yearly mean sunspot number. It is seen from the diagram that D/Q ratio during the J-months is always greater than unity fo any of the years, the values being generally around 1.0 and there being no apparent solar cycle variation On the other hand the ratio during the D-months was lower during high sunspot years, and decreased below the value of 1.0 during the years 1957 to 1960 indicating lower critical frequency during disturbed days. It is thus concluded, that out of al available data at Huancayo, this abnormality o low critical frequency during magnetic storms wa confined only to the IGY/IGC period, which happen to be the most prominent sunspot maximum period so far.

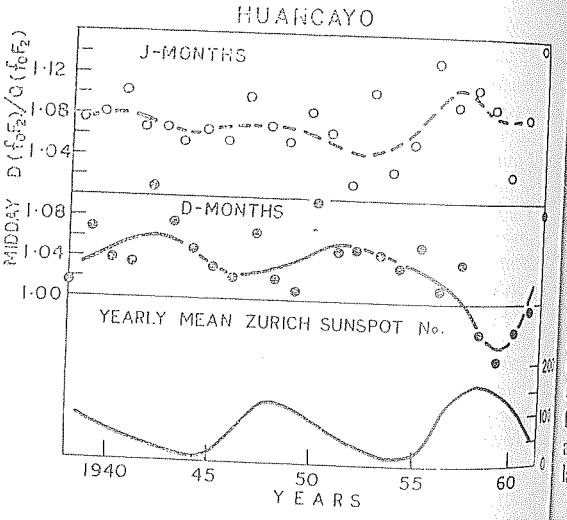


FIG. 1.

Solar cycle variation of the ratio of midday mean f_0F_2 o Disturbed and Quiet days of J and D months at Huancay for the period 1938-1962.

To study the behaviour of the F_2 region at differe heights during comparatively low sunspot year N-h profiles were computed for midday hours of fi International Quiet days and five Internation Disturbed days of winter and summer months at t equatorial station, Huancayo, medium latitude statio Puerto Rico, and at high latitude station, Fo Monmouth, and these are shown in figure 2.

J. A., fasc. 4, 1968

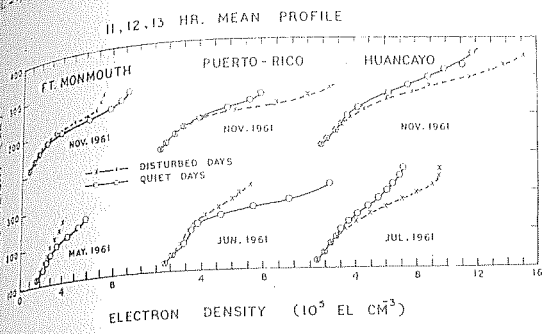


FIG. 2.

The profiles of electron density versus true height N-h in the ionosphere during the midday hours on Quiet and Disturbed days of a northern and a southern solsticial month of 1961 at equatorial (Huancayo), tropical (Puerto Rico), and high-latitude (Fort Monmouth) stations.

At Fort Monmouth, the average electron densities are higher during November than during May. This represents the well-known seasonal anomaly of higher f_0F_2 occurring during winter than during summer. It is interesting to note that the heights of maximum electron density are not appreciably different during the two seasons, indicating that the electron density at any of the heights, are lower during summer than in winter, at high latitudes. Comparing the profiles on quiet and disturbed days, it is seen that the values are not significantly different from each other for levels ranging from 100 to 180 km. At heights above 200 km there is a definite decrease of electron density during the disturbed days, than during quiet days in either of the two seasons, maximum change occurring at the height of F_2 peak. Regarding the profiles at Huancayo, we again find that the average electron density at any particular height is greater during November than during the July month. This indicates that besides abnormal seasonal variation, there is an annual effect causing greater ionisation during December solstices than during June solstices [RASTOGI, 1960]. Comparing the profiles during quiet and disturbed days, one finds little change below the levels of 180 km while at any of the higher levels the ionisation is much larger on disturbed than on quiet days.

Regarding the variations at mid-latitude station, Puerto Rico, it is seen that again the magnetic disturbances affect the ionosphere only above 180 km. During the winter month of November 1961, the electron density seems to increase during disturbances, while during summer months there is a prominent decrease of electron density during disturbed days from about 200 km height. These changes in the electron densities at any of the stations and during any of the seasons are noticeable for the heights above 180 km, which means above the height of the F_1 peak. This confirms MATSUSHITA'S result [1962] for Puerto Rico, that the change during magnetic storms occurs at levels only above 200 km.

It is thus concluded that the results of previous investigators based on f_0F_2 (proportional to maximum electron density) is confirmed for electron density at individual heights of the F_2 region. Thus the magnetic disturbance causes the decrease of electron density at each height of the F_2 layer during summer as well as winter at high latitudes; it increases the electron density at all heights during winter or summer for equatorial stations; while at medium latitude stations the magnetic storm effect on N-h profiles is of the equatorial type during winter, and of high latitude type during summer.

The maximum ionisation of the F_2 layer ($N_{\max}F_2$) the height of maximum ionisation ($h_{\max}F_2$) and the totally integrated electrons over a vertical column of unit cross section (N_T), for each of the solar hours on the quiet and disturbed days of summer and winter months were studied at Fort Monmouth, Puerto Rico and Huancayo. The daily variation of these parameters on quiet and disturbed days is shown in figure 3. The circles indicate the quiet days, while the crosses indicate the disturbed day values.

The height of maximum ionisation ($h_{\max}F_2$) shows a maximum during midnight, and minimum during midday hours at medium and high latitude stations (Puerto Rico and Fort Monmouth) while at equatorial stations, it is maximum in the afternoon hours and is lower during the night hours, in confirmity with the conclusions of WRIGHT [1962]. The maximum electron density at Fort Monmouth shows a maximum during midday, this being sharper in winter, and relatively flatter during the summer months. At Puerto Rico, the daytime maximum is close to midday during winter, but is shifted to the evening hours during summer months. At Huancayo there is a pronounced broad daytime maximum and the well-known bite-out effect at the equatorial stations is not evident.

Referring to Fort Monmouth it is seen that $N_{\max}F_2$ is lower on disturbed days than on quiet days of winter for the hours, 06 to 12, while during the summer months on disturbed days, it is very significantly lower than that on quiet days for almost all the hours from 06 to 24. The height $h_{\max}F_2$ is slightly higher on disturbed days during winter months, and smaller during summer months, the changes being very small. The total electron content N_T shows very small effect during winter and significant decrease during the disturbed days of summer. Thus, the effects of magnetic storms on high latitude F_2 region seem to be most pronounced during the daylight hours and especially during the summer months. Regarding the profiles of Puerto Rico, it is seen that during the winter months of November 1961, both $N_{\max}$ and N_T are much larger on disturbed days than on quiet days for the daylight hours, the effect being too small for night hours 00 to 06 hours. The height $h_{\max}F_2$ seems to have increased during the magnetic storms. During summer months of June 1961 the $N_{\max}F_2$

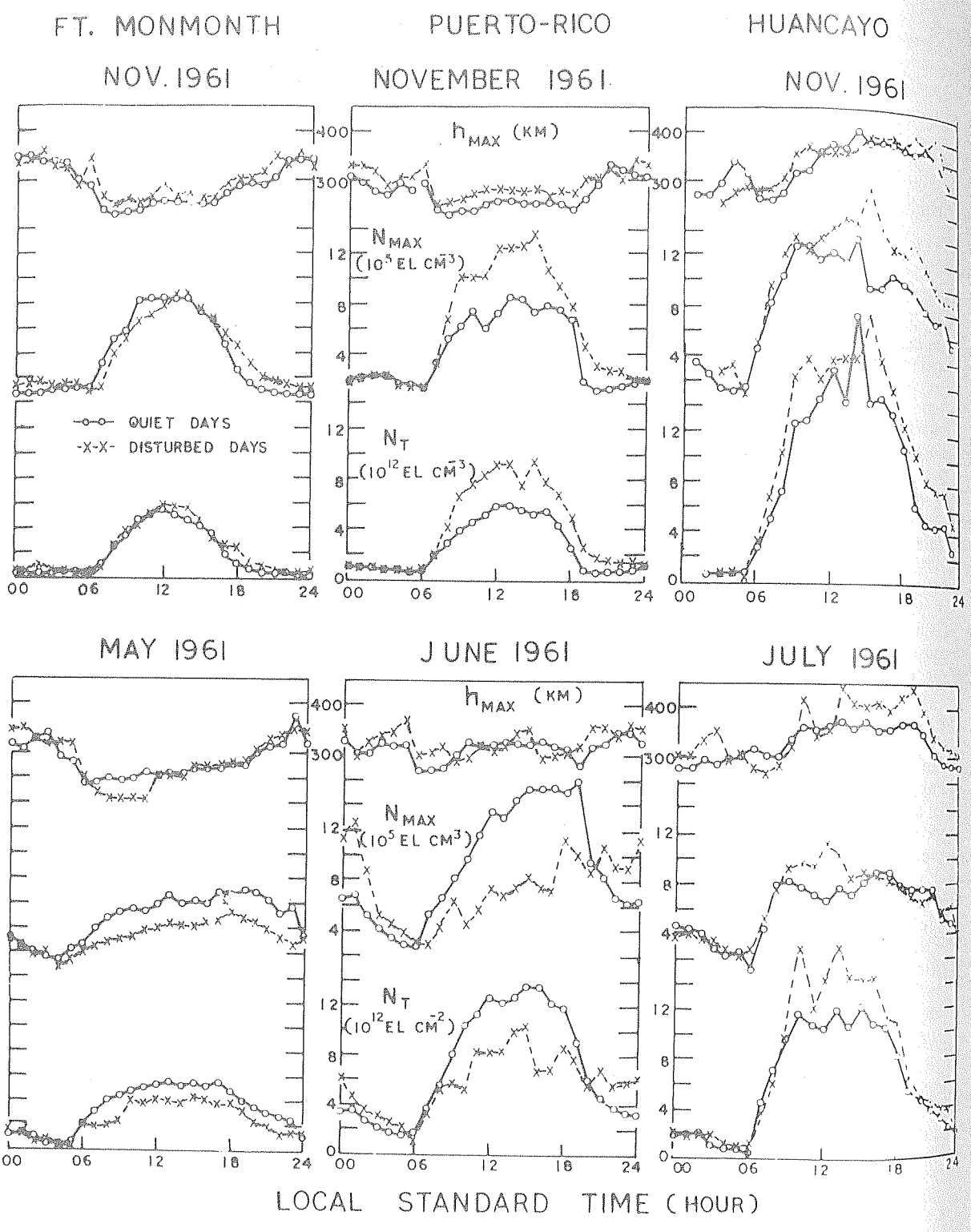


FIG. 3.

Daily variations of height of maximum ionisation ($h_{max}F_2$) maximum electron density ($N_{max}F_2$), and total electron content in a vertical column of unit cross-section (N_T) on Quiet and Disturbed days of a northern and a southern solsticial month of 1961 at Huancayo, Puerto Rico and Fort Monmouth.

24, fasc. 4, 1968

as well as N_T have decreased for the hours 06 to 20. The slight increase during the night hours 20 to 06 is also clear. There is no distinct effect in $h_{max}F_2$.

Regarding Huancayo it is seen that in general there is an increase of $N_{max}F_2$ during disturbed days of either summer or winter, although the effect is more pronounced during the daytime hours. The effect on $h_{max}F_2$ is again small and uncertain.

SKINNER and WRIGHT [1955] have studied the variations of parameters of the F_2 layer at Ibadan during magnetically quiet and disturbed days, and they have found that $N_{max}F_2$ is larger on disturbed than on quiet days. For any of the hours correspondingly, N_T is also greater on disturbed than on quiet days. They have found that the base of the F_2 layer $h'F_2$ is lowered during the daytime hours of disturbed days, but $h_{max}F_2$ is decreased on disturbed days, between 08 to 13 hours and increased between 13 to 19 hours. The midday minimum of $N_{max}F_2$ seemed to disappear as magnetic conditions became more disturbed. Thus the variations of the F_2 layer parameters at Huancayo during 1961, are very similar to that found at the equatorial station, Ibadan.

Having found the normal expected variation of the disturbed F_2 layer during the relatively quiet period of 1961, the elctron density profiles of one summer and one winter month were computed from the ionograms for the equatorial stations, Huancayo and Chimbote. The mean N-h profiles over 11, 12 and 13 hours are shown in figure 4. The diagram shows profiles of July and November 1957 for Huancayo, and July and November 1958 for Chimbote. It is seen that the $N_{max}F_2$ at both Huancayo and Chimbote are larger during November than during July months. Comparing the mean profiles during July and November months, it seems that during 1957 at Huancayo, the electron densities were not appreciably different during the two seasons upto 300 km and there was additional ionisation till about 400 km which gave rise to much higher $N_{max}F_2$. During 1958 at Chimbote, the electron density seems to be higher in November than in July for any of the heights, the change being more at greater heights. Thus, the larger cri-

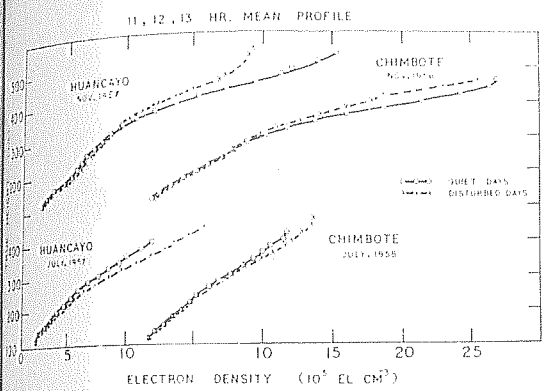


FIG. 4.

N-h profiles for midday hours on Quiet and Disturbed days of July and November months of IGY at equatorial stations Huancayo and Chimbote.

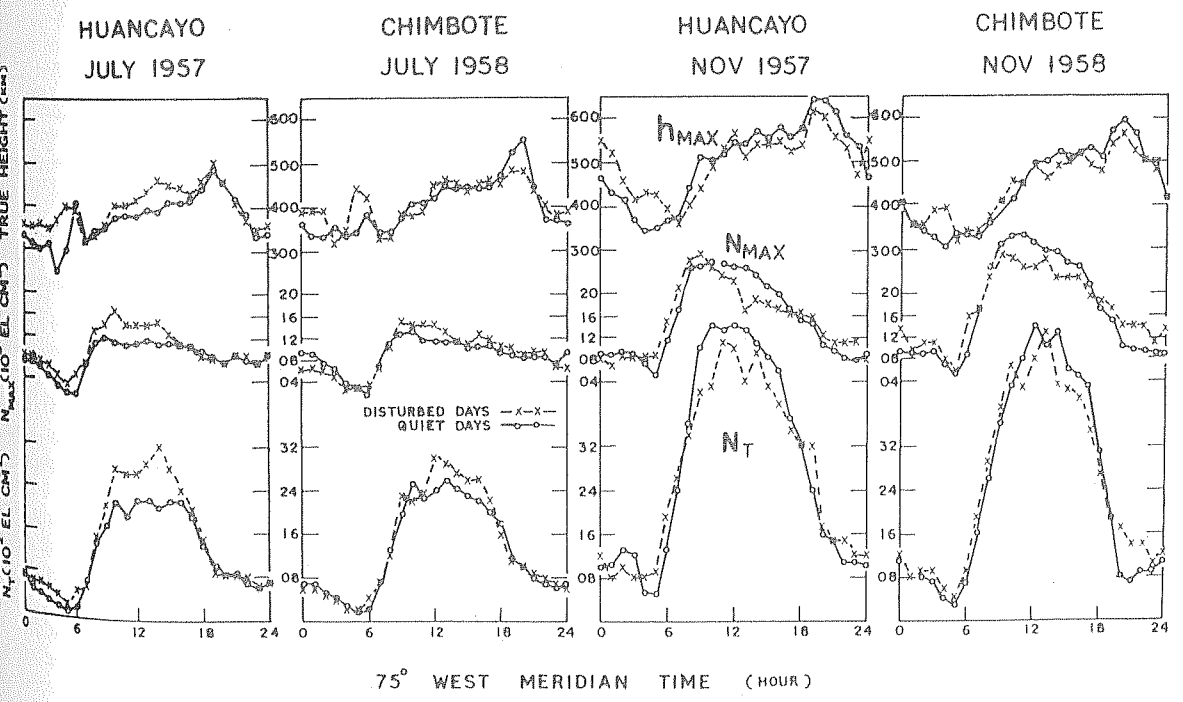


FIG. 5.

Daily variations of $h_{max}F_2$, $N_{max}F_2$ and N_T on Quiet and Disturbed days of July and November months of IGY, at Huancayo and Chimbote.

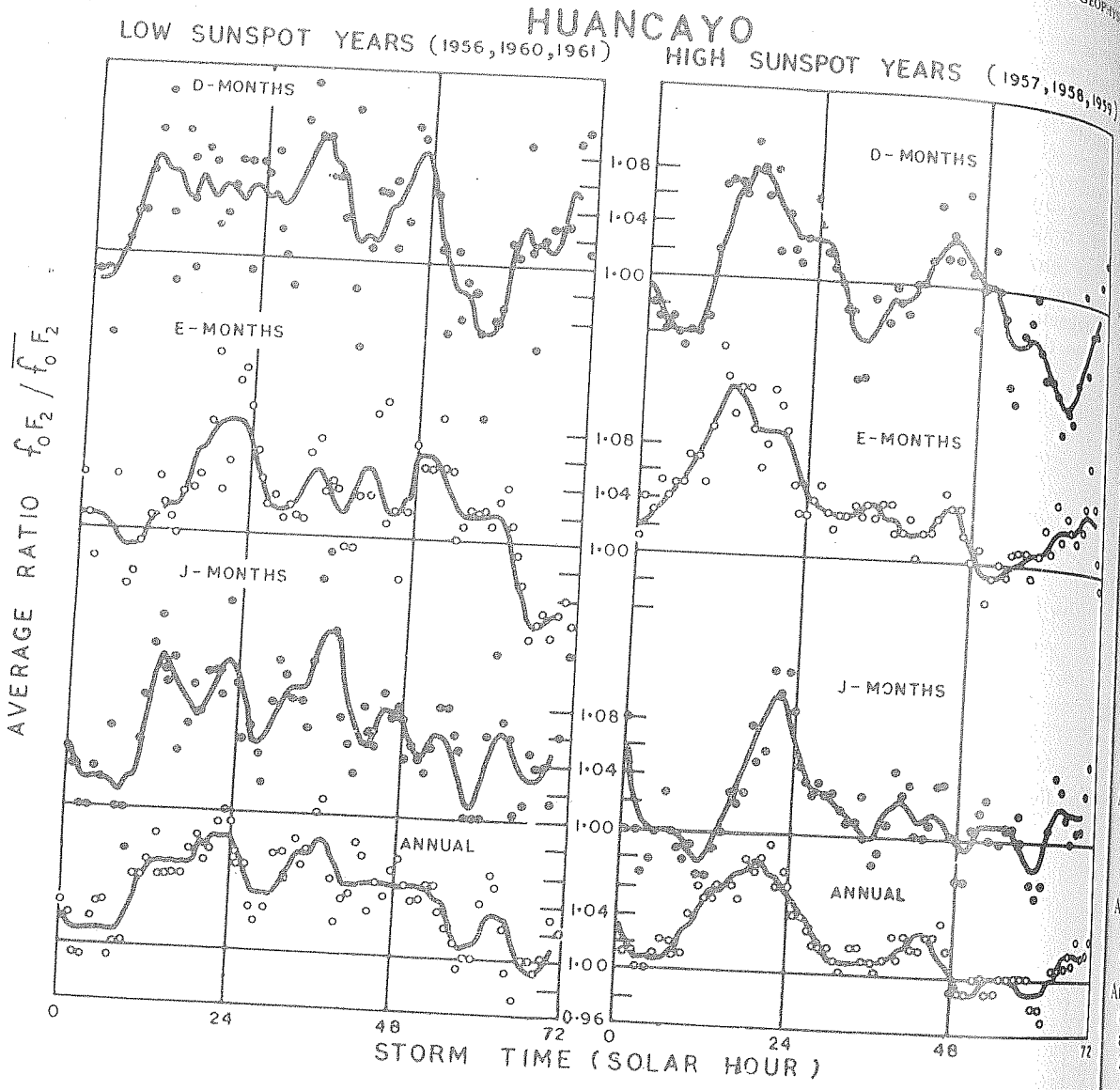


FIG. 6.
Storm-time variations of f_0F_2 during D, E, J and all months at Huancayo during years of low and high solar activity.

tical frequency during November months, is either due to increase of the height of the F_2 layer, or absolute increase of the electron density at the same heights. Comparing the profiles on disturbed and quiet days during the July months, one finds the electron densities to be higher on disturbed than on quiet days for both Huancayo and Chimbote, the effect being more pronounced at greater heights. During the month of November, the electron densities at either Huancayo or Chimbote are slightly higher on disturbed than on quiet days upto a height of about 300 km but, at heights above this, electron densities are decreased on disturbed days. Thus the abnormal decrease of the ionisation at the equatorial stations during the D-months of IGY/IGC period seems to take place close to the peak of the F_2 layer.

In figure 5 are compared the solar daily variation of $h_{max}F_2$, $N_{max}F_2$ and N_T during the July-Novembe months at Huancayo and Chimbote. Referring the curves for the July months it is seen that N_{max} and N_T during the daytime hours are higher on dis turbed than on quiet days, and the effect is small a uncertain during the night hours. The height h_{max} has a tendency to be slightly higher on the disturbe than on the quiet days. During the November mont the decrease in N_T and $N_{max}F_2$ during the disturbe days is again significant during the midday hou while changes in $h_{max}F_2$ during the daytime are unce tain. These results indicate that the decrease or i increase in $N_{max}F_2$ is not basically due to the chan in the level of peak f_0F_2 but all the heights near t peak are affected similarly.

It was felt desirable to see the effect of abnormal disturbed daily variations, and the storm time variation, and hence D_{st} variations in f_0F_2 at Huancayo were computed for the three seasons D-months (November, December, January and February), E-months (March, April, September and October) and J-months (May, June, July and August) both for the low sunspot years 1956, 1960 and 1961, and for the high sunspot years 1957, 1958 and 1959 (fig. 6). It is seen that during any of the seasons and epochs, the D_{st} variation of f_0F_2 at Huancayo is basically of a positive type. There are, however, large variations during the D-months of the high sunspot years, there being a small negative phase on the 2nd and 3rd days which could be due to remnant disturbance daily variation.

It is however interesting to note that the annual average D_{st} variation, expressed here in terms of the ratio of f_0F_2 on the disturbed day over the corresponding mean value, is more pronounced during the low, than during the high sunspot years. This means that the magnetic storm effects produce comparatively larger proportional changes in the electron density of the F_2 layer at the equatorial stations, during the low than during the high sunspot years. Further the positive phase of the storm seems to remain for a larger period i.e. up to about 2 1/2 days during the low sunspot years, whereas it comes to normal value in about 1 1/2 days during the high sunspot period. Further analyses are contemplated to study the solar cycle variations of D_{st} in f_0F_2 at equatorial stations.

Acknowledgments

Sincere thanks are due to the Institute of Telecommunication Sciences and Aeronomy at Boulder, for making available the ionograms and other data, which have been used for this study, and to Professor K. R. Ramanathan, for suggestions and discussions during the course of the study.

Manuscrit reçu le 9 septembre 1968.

REFERENCES

Appleton E. V. and Ingram L. J., "Magnetic storms and upper Atmospheric ionisation," *Nature*, Lond., 136, 548-549, 1935.

Appleton E. V., Naismith R. and Ingram L. J., "British Radio Observations during second International Polar Year 1932-1933," *Phil. Trans. Royal Soc.*, A236, 191-259, 1937.

Appleton E. V. and Piggott W. R., "Morphology of storms in the F_2 layer of the ionosphere," *J. Atmos. and Terres. Phys.*, 2, 236-252, 1952.

Appleton E. V. and Piggott W. R., "Storm Phenomena and Solar Cycle Variations of the F_2 layer ionisation at noon," *Physics of the Ionos. Phy. Soc. Lond.*, 219-228, 1955.

Berkner L. V. and Seaton S. L., "Systematic Ionospheric Changes associated with geomagnetic activity," *Terr. Mag. and Atmos. Elec.*, 45, 419-423, 1940.

Bhargava B. N. and Rao U. V. G., "Ionospheric disturbances associated with magnetic storms at Kodaikanal," *Ind. Journal of Met. Geophys.*, 10, 203-208, 1959.

Harang L., "Störungen der Ionosphäre und der Funkausbreitung während der Nordlichter und erdmagnetischen Störungen," *Geophys. Publikasjoner*, 11, n° 17, 1-55, 1937.

Martyn D. F., "Morphology of ionospheric variations associated with magnetic disturbances," *Proc. Roya Soc.*, A218, 1-18, 1953.

Matsushita S., "A study of the morphology of ionos. storms," *J. Geophys. Res.*, 64, 305-321, 1959.

Matsushita S., "Ionospheric variations during geomagnetic storms," *Proc. of the Internat. Conf. on Ionos.*, Imperial College, Lond., 1962.

Obayashi T., "Some characteristics of ionospheric storms," *Rep. Ions. Res., Japan*, 6, 79-84, 1952.

Rastogi R. G., "Asymmetry between the F_2 region of the ionosphere in the Northern and Southern hemispheres," *J. Geophys. Res.*, 65, 857-868, 1960.

Rastogi R. G., "The effect of geomagnetic activity on the F_2 region over Central Africa," *J. Geophys. Res.*, 67, 1367-1374, 1962.

Rastogi R. G. and Rajaram G., "Abnormal behaviour of f_0F_2 in magnetically active periods of IGY-IGC," *J. Atmos. Terr. Phys.*, 27, 1097-1103, 1965.

Skinner N. J. and Wright R. W., "Some geomagnetic effects in the equatorial F_2 region," *J.Atmos. Terr. Phys.*, 6, 177-188, 1955.

Wright R. W., "Diurnal and seasonal changes in structure of the mid-latitude quiet ionosphere," *Journal of Res. NBS*, 66D, 297-312, 1962.

4.7 EQUATORIAL ELECTRON DENSITY DISTRIBUTIONS DURING QUIET AND DISTURBED CONDITIONS

Comparisons of electron density distributions on International Quiet and Disturbed days for different seasons and different solar cycle epochs have been made by considering the following equatorial stations:-

Huancayo	-	dip + 2° (West Zone)
Thumba	-	dip 0.6° (East Zone)
Kodaikanal	-	dip + 3.5° (East Zone)

The true height profiles were computed from the ionograms for the stations by using Budden's Matrix method. The diurnal variations of h_{max}, y_m, N_T and N_{max}, the contours of constant electron density, and electron density distributions at constant heights, have been taken into consideration in making comparisons between magnetically Quiet and Disturbed days.

(a) Studies at Thumba

i) Variations of $h_{max}F_2$, y_m, N_T, $N_{max}F_2$

Fig. 4.11 (Pg. 101 (a)) shows the variations of h_{max}, y_m, N_T and N_{max} on quiet (Q) and Disturbed (D) days for 3 typical seasons - January (winter), April (Equinox), and July (Summer). The variations are shown for 1967 (a high sunspot year R_z = 96) and 1965 (a low sunspot year R_z = 15).

TRIVANDRUM-1965
JAN
APRIL
JULY
LOCAL TIME IN HOURS
QUIET DAYS(Q)
DIST DAYS(D)
N_{MAX} IN 10^5 EL/CM^3
N_T IN 10^5 EL/CM^3
Y_M IN KM
H_{MAX} IN KM

TRIVANDRUM-1967
JAN
APR
JULY
LOCAL TIME IN HOURS
INTERNATIONAL QUIET DAYS (Q)
INTERNATIONAL DIST DAYS (D)
N_{MAX} IN 10^5 EL/CM^3
N_T IN 10^5 EL/CM^3
Y_M IN KM
H_{MAX} IN KM

FIG 5

101(a)

It is clearly seen that:

(1) In Jan. and April 1967, there is a post-sunset rise in $h_{max}\ F_2$ which seems slightly less on D days than that on Q days. This point could be significant in throwing light on the cause of the equatorial post-sunset height rise. In July 1967, this feature is not seen on either Q or D days. It is not seen in any season of 1965. In 1967 January and July, $h_{max}\ F_2$ on D days is less than on Q days, but this is not clear in April. In 1965 the reverse seems to occur, true heights on D days being greater than on Q days. Overall values of $h_{max}\ F_2$ are larger in 1967 than in 1965.

(2) The variations of y_m show that the semi-thickness reaches it maximum values shortly before midday, during both Q and D conditions in every season in both years.

In the low sunspot year of 1965, there are clear differences in y_m between Q and D. In April and July, the semithickness on D days is greater than on Q days, but in January in the daytime hours, values of y_m on D days are less than those on Q days. Overall values of y_m too are larger in 1967 than in 1965.

(3) Variations of N_T differ more between Q and D days in 1965 than in 1967. In general, in 1965, N_T on D days is more than on Q days in all seasons. The same is true of

N_{max}. Since both N_T and N_{max} show an increase, the F_2 layer is not merely being compressed so as to increase peak ionisation densities. A real absolute increase in the total number of electrons is taking place during disturbed conditions.

In 1967, the variations of N_T and N_{max} F_2 do not differ much between Q and D conditions in any season. Only in the equinox (April) does it appear clearly that both N_T and N_{max} F_2 are greater on D than on Q days. In January, D values seem slightly less than Q values in the daytime hours, while nothing can be said of July. The midday bite-out feature in N_{max} F_2 is seen in all seasons of 1967, and April and July 1965, but it is not clear in January 1965. Clearly absolute values of N_T and N_{max} F_2 are more in 1967 than in 1965.

(ii) Iso-electron density contours during quiet (Q) and Disturbed (D) days.

These studies are made for the Q and D days of the same three representative months at Thumba and are shown in Fig. 4.12 (Pg.106 (a))

Considering overall behaviour of the two sunspots, it is seen that:

(1) There is a greater crowding together of contour lines because of larger electron densities in high sunspot than in low sunspot. This is true of all heights above 200 km; levels below this are not appreciably affected. The change in peak electron density from low to high sunspot can be seen from the diagrams and differs almost by a factor of 2. During Quiet conditions afternoon peak values change thus -

Electron density in el/cm^3

Month	Afternoon peak (low sunspot)	Afternoon peak (high sunspot)
January	6×10^5	12×10^5
April	10×10^5	16×10^5
July	6×10^5	12×10^5

During Disturbed conditions the changes are -

Electron density in el/cm^3

Month	Afternoon peak(low sunspot)	Afternoon peak(high sunspot)
January	7×10^5	12×10^5
April	10×10^5	17×10^5
July	7×10^5	14×10^5

(2) The sharp height gradient of iso-electron density contours around sunrise and sunset (around 06 hr and 18 hr) is more marked in high sunspot than in low. The steep post-sunset rise in heights is absent in the low sunspot years, and is more marked in January and April of high sunspot, not in July.

(3) In low sunspot years, particularly on Q days, ionisation before sunrise falls to levels too low to be detected by the ionosonde. This feature is not so in high sunspot years when a good amount of ionisation persists even before sunrise.

(4) In low sunspot years, both on Q and D days, peak heights of ionisation are attained in the midday hours. In high sunspot years, they occur after sunset.

These are a few of the solar cycle differences in electron density distributions at Thumba. A detailed study of these solar cycle differences on Q days at Thumba is presented by Chandra (1969) in his Ph.D. thesis.

Comparing the density distribution on Q and D days from the same figure, the salient features are:-

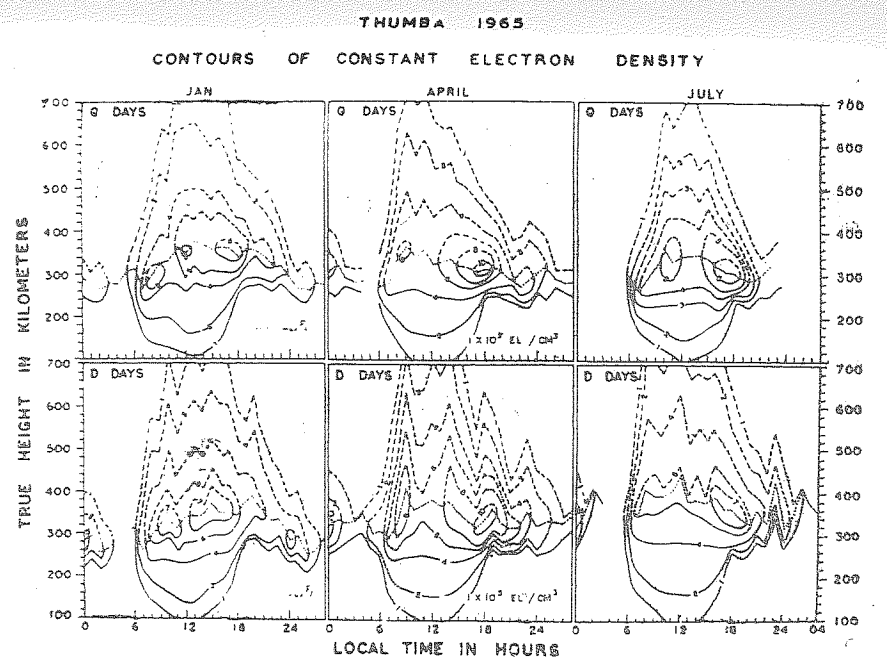
(1) There are greater electron densities on D days as compared to Q days. This is true of both high and low

sunspot years at heights above 200 km - levels below this seem unaffected by magnetic disturbances. An exception to these observations are the D days of July 1965, where the contours are farther apart than on Q days. This may be due to greater height distributions of ionisation on D days in July. It may be noted that h_{max} F_2 on D days is on an average greater than on Q days by almost 50 km.

(2) There has been an enormous and sudden height rise after 18 hr in the Q days of April 1967 followed by spread-F conditions. It may be noted that in the D days of the same month, the post-sunset height rise is less sudden and of less magnitude, and no spread-F is seen. It is known that at equatorial stations, spread-F is less on D Days than on Q days; hence its occurrence may be related to this height rise.

(iii) Electron density distribution at constant heights.

In Fig. 4.13 (Pg.106 (a)) the electron density distributions at constant heights at Thumba are compared between Q and D days for the January, April, and July months of 1967 and 1965. On the average, electron densities on D days are greater than on Q days, in each season of both sunspots (except in January 1967) and the midday bite-out feature too seems to be reduced on D days. The afternoon peak seems to broaden out on D days as compared to Q days



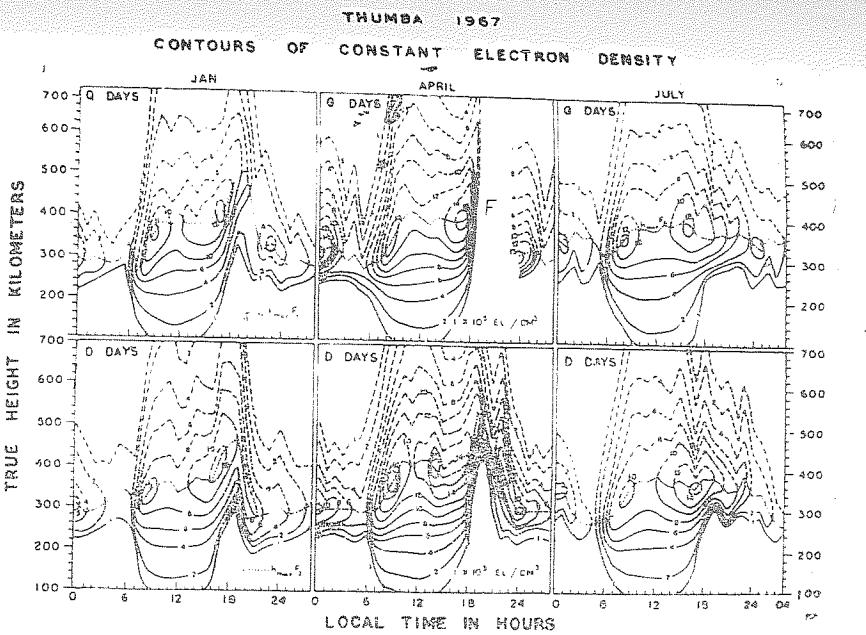


Fig. 4.12

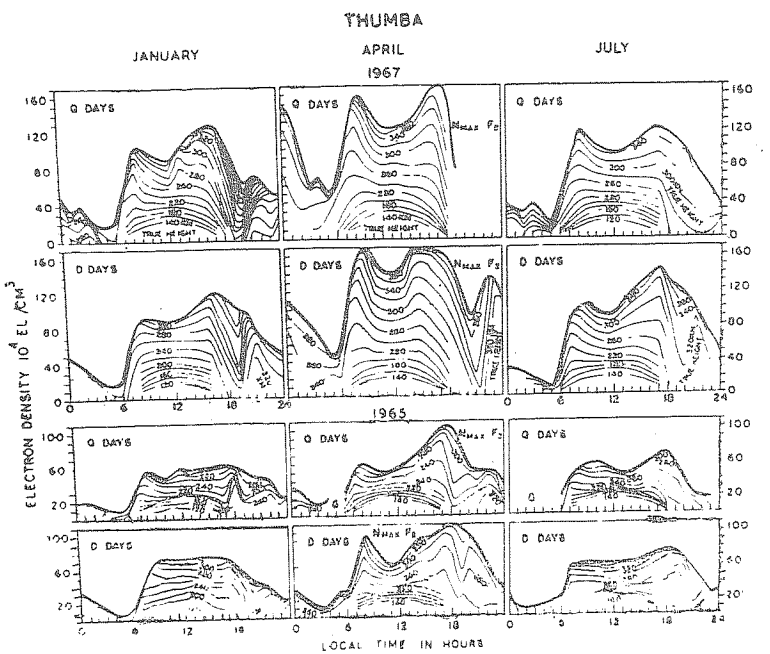


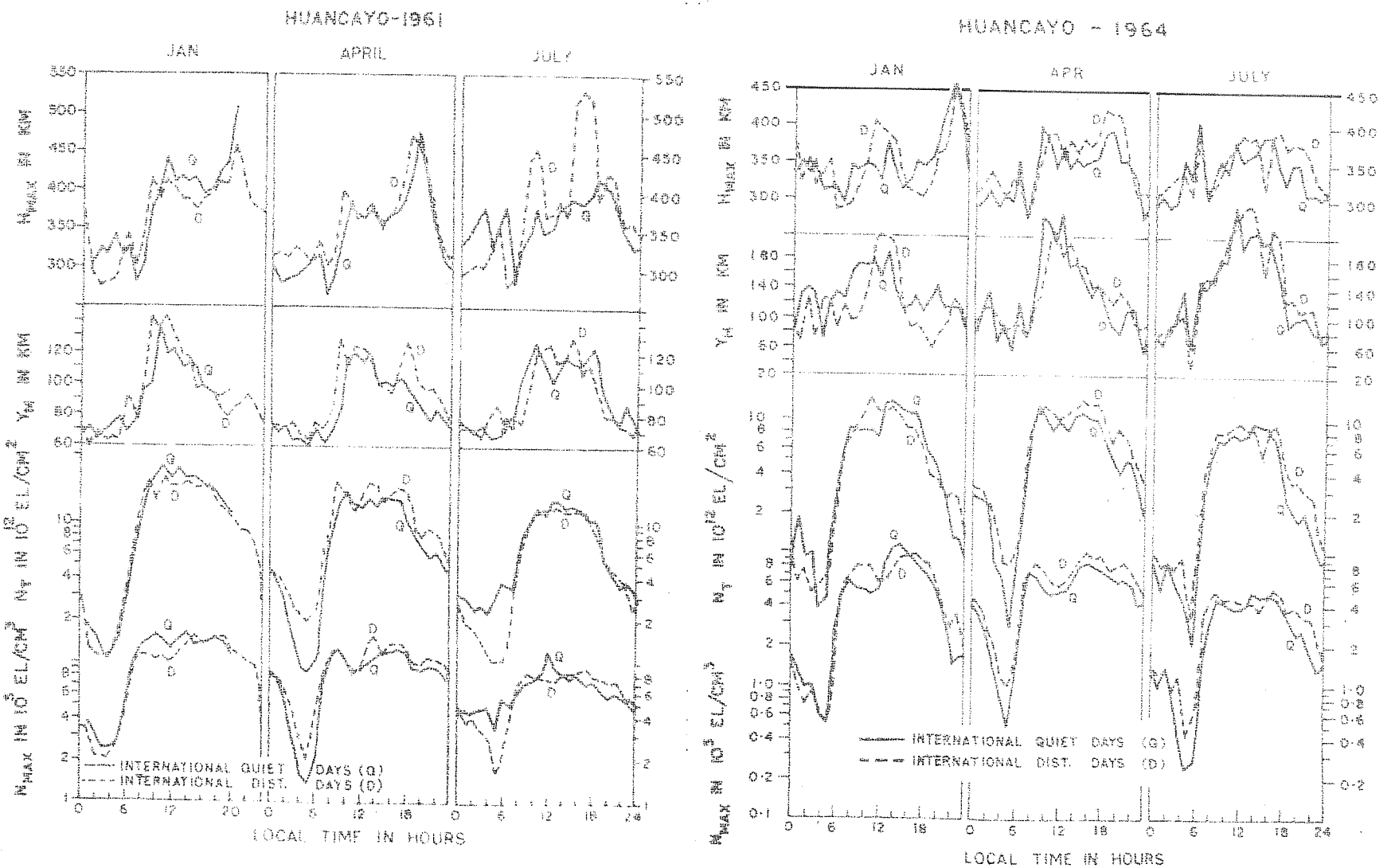
Fig. 4.13

particularly at greater heights. Some of the more minute differences can be observed from the figure itself. The markedly lower electron densities in 1965 (a low sunspot year) as compared to 1967 (a high sunspot year) can be clearly seen. It is clear that in 1967, up to a height of 180 km the electron density varies with a simple Chapman behaviour with peak values around midday. At heights above this the day time bite-out in electron density starts manifesting itself. In 1965, such bite-out is seen only at levels above 220 km. The level at which bite-out commences therefore, seems to be a function of solar cycle, being lower in high sunspot, and higher in low sunspot.

(b) Electron density studies on Q and D days at Huancayo.

(i) Variations of h_{max} F_2 y_m, N_T, N_{max} F_2

Variations of h_{max}, y_m, N_T and N_{max} for the same seasons - January (summer), April (equinox), and July(winter), are shown for Huancayo ($12^{o}S$ geographic) in the American zone. The years chosen are 1961 - a medium sunspot year (R_z = 54) and 1964 - a low sunspot year (R_z = 10) and the variations are shown in Fig. 4.14 (Pg. 107(a)).


HUANCAYO-1961
JAN
APRIL
JULY
N_{MAX} IN KM
Y_M IN KM
N_{MAX} IN 10^5 EL./C.M.^{3} N_T IN 10^{12} EL./CM.^{2}
INTERNATIONAL QUIET DAYS (Q)
INTERNATIONAL DIST. DAYS (D)
LOCAL TIME IN HOURS
HUANCAYO - 1964
JAN
APR
JULY
H_{MAX} IN KM
Y_M IN KM
N_T IN 10^{12} EL/CM.^{2}
N_{MAX} IN 10^5 EL/CM.^{3}
INTERNATIONAL QUIET DAYS (Q)
INTERNATIONAL DIST. DAYS (D)
LOCAL TIME IN HOURS

107(a)

Fig 4·14

A study of the variations reveals:

(1) In January and April of both 1961 and 1964 there is a post-sunset rise in $h_{max}\ F_2$. It is not present in July of either year; the sharp rise on D days of July 1961 seem spurious, and may be due to insufficient data. It is difficult to come to any conclusions on the variations in $h_{max}\ F_2$ between Q and D days. In both years in April and July, heights on D days seem to exceed heights on Q days, while in January, overall heights seem to be less on D days except for a few hours around midday in 1964. It is difficult to say anything about the relative magnitudes of the post-sunset rise on Q and D days. Overall $h_{max}\ F_2$ is larger in 1961 than in 1964.

(2) Variations of y_m show more differences between Q and D in 1961 than in 1964. The trend is the same, with semi-thickness reaching minimum values around 06 hr. and maximum values at or shortly before midday. One gains a general impression that y_m is slightly greater on D days than on Q days in all seasons of 1961, while in 1964 there seems little difference between the two.

(3) Both $N_{max}\ F_2$ and N_T are larger in 1961 than in 1964. It is difficult to say much about the trend of N_T and N_{max} on Q and D days. In 1961 in January, D values are less than Q; in April D values exceed Q. There is

uncertainty in July. In 1964, D values exceed Q in April (equinox), but uncertainty prevails in both January and July. As far as N_{max} F_2 is concerned, only the equinoctial months of both years follow the accepted ideas of disturbances increasing F_2 electron densities at the equator. The behaviour in Jan. 1961 of disturbed N_{max} F_2 being less than quiet N_{max} F_2 is rather unexpected. The fact that N_T has also decreased shows that the decrease has been due to a real loss of ionisation, and not merely to changes in the ionisation peak height. It may be noted that Disturbed N_{max} and N_T were less than Quiet N_{max} and N_T in January 1967 at Thumba too. This arouses a feeling that equatorial stations have a tendency to show a decrease in ionisation during disturbed conditions notably in the December solstitial months. Why this should be is not understood, and needs investigation.

(ii) Iso-electron density contours on Q and D days.

These studies are made for Huancayo for the Q and D days of the three months January, April and July of the low sunspot year 1964 (Fig. 4.15) (Pg. 109 (a)) and the outstanding features are:-

(1) Least crowding of contours and smallest electron densities occur in July; this is true of both Q and D days.

(2) The sharp increase in ionisation at sunrise (around 06 hr.) is seen in all seasons on both Q and D days. A sharp drop in ionisation at sunset (around 18 hr) is however seen only in April.

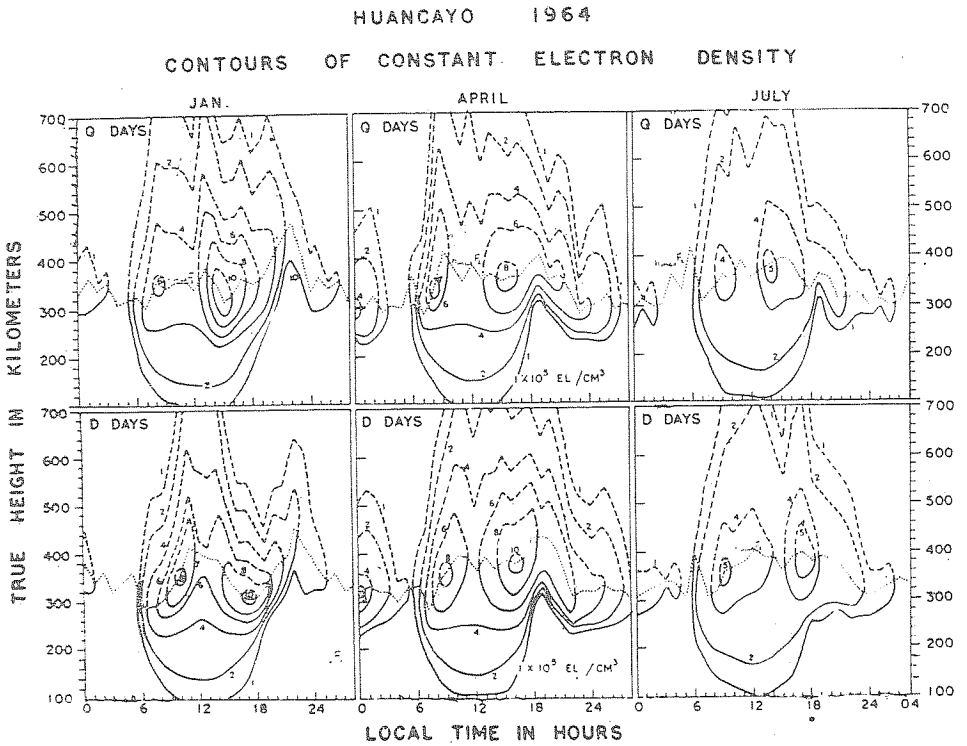


Fig. 4.15

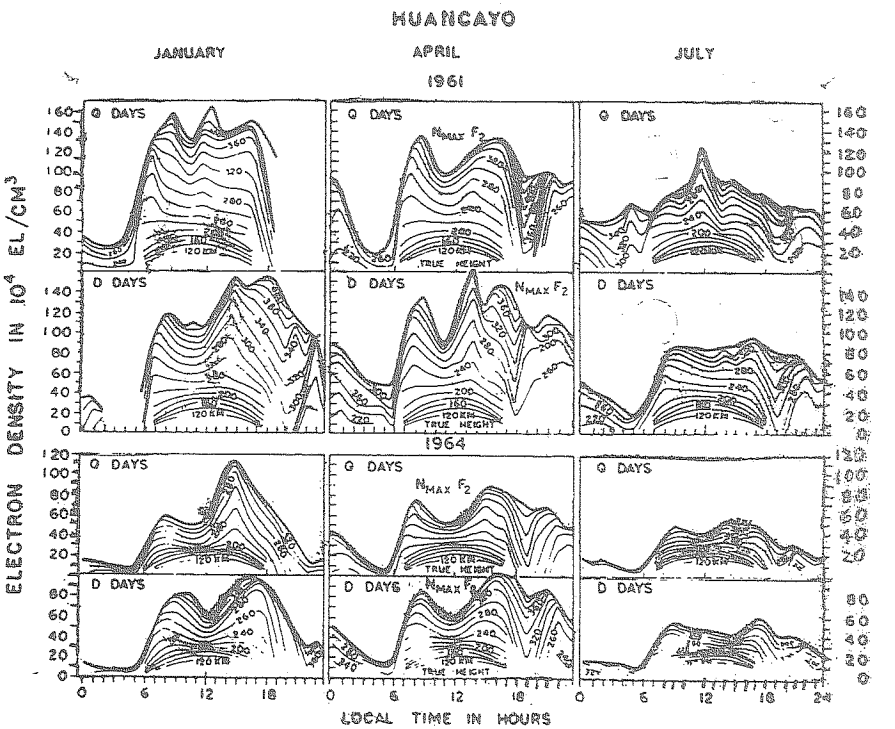


Fig. 4.16

Fig. 4.14 (Pg. 107 (a)) showed that a substantial change in $N_{max}\ F_2$ between Q and D days is clear only in April 1964, but is not obvious in January and July 1964. A closer look at Fig. 4.15 (Pg. 109 (a)) shows that even in 1964 the change is in the forenoon peak rather than in the afternoon peak. The forenoon peak electron densities change thus

1964 - Forenoon peak electron density in el/cm^3

Month	Quiet	Disturbed
January	6×10^5	8×10^5
April	7×10^5	8×10^5
July	4×10^5	5×10^5

Afternoon peak electron densities change only in April between Q and D days in 1961.

(4) No post-sunset rise in ionisation height is seen in any season either on Q and D days for this year. Clearly this feature is characteristic of high sunspot only.

(iii) Electron density distributions at constant height during Q and D conditions .

These variations at Huancayo are compared for Q and D days for the same three seasons of 1961 and 1964 in Fig. 4.16 (Pg. 109 (a).

The electron densities on D days are larger than on Q days particularly in the afternoon hours; in January 1961 the forenoon peak has decreased on Q days. The finer details can be seen from the diagram itself. The feature of lower electron densities in 1964 (a low sunspot year) as compared to 1961 (a medium sunspot year) is clear. The midday bite-out in $N_{max}\ F_2$ is more prominent in 1964; in 1961, there is an unconventional midday peak in $N_{max}\ F_2$. The daytime bite-out in electron density commences above heights of 200 km. in January and April. In July there is no clear bite-out even at the $N_{max}\ F_2$ level in 1964, and very little in 1961. Specific differences between the two years in the levels at which bite-out commences are not obvious.

4.8 Longitudinal differences in Quiet and Disturbed-day behaviour of equatorial electron density distributions (Kodaikanal and Huancayo)

Comparisions of magnetically Quiet and Disturbed conditions for identical periods of high sunspot were made for the equatorial stations, Kodaikanal (East zone) and Huancayo (West zone), to see how the widely -differing geomagnetic field characteristics at the two locations would affect the electron density distributions with height .

(a) Comparison of $h_{max}\ F_2$, y_m, N_T, $N_{max}\ F_2$

Fig 4.17 (Pg. 112 (a) shows the variations of h_{max}, y_m, N_T and N_{max} on Q and D days at these two stations for July 1957, 1958, and November 1957, 1958. Being equatorial stations it was believed that seasonal effects would not enter too much in the picture.

(1) $h_{max}\ F_2$ variations

Peak F_2 heights seem larger at Kodaikanal than at Huancayo, and the difference is larger in July (almost 100 km) and less in November (about 50 km) of both years. The post-sunset rise in height too is more prominent at Kodaikanal than at Huancayo. This fact could be of importance in deciding the part played by electric fields in the height-rise. At both places, minimum $h_{max}\ F_2$ values occur around around 06 hr. and maximum after 18hr. In 1958, there is little difference in $h_{max}\ F_2$ between Q and D days, at both places - only Kodaikanal in July 1958 shows D values to be slightly greater than Q.In 1957 , differences are clear at both locations. In July 1957 D values of $h_{max}\ F_2$ are greater than Q values at almost all hours of day at both stations. In November 1957, D values of $h_{max}\ F_2$ are less than on Q days at both stations, and it is acompanied by a decrease in both $N_{max}\ F_2$ and N_T on D days at both locations.

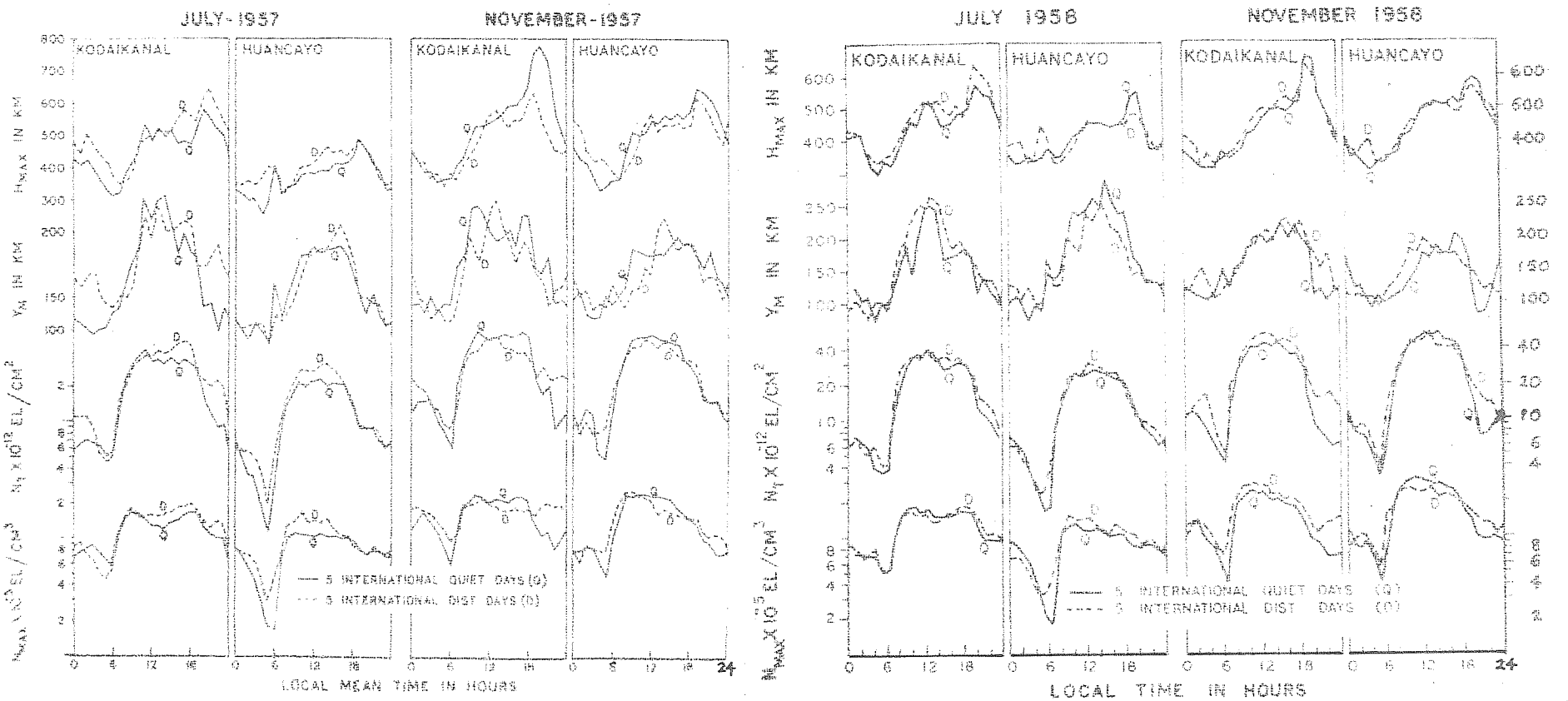

JULY-1957
NOVEMBER-1957
JULY 1958
NOVEMBER 1958
KODAIKANAL
HUANCAYO
h_{MAX} IN KM
Y_M IN KM
$N_T \times 10^{12}$ EL/CM^2
$h_{MAX} \times 10^{-5}$ EL/CM^3
5 INTERNATIONAL QUIET DAYS (Q)
5 INTERNATIONAL DIST DAYS (D)
LOCAL MEAN TIME IN HOURS
LOCAL TIME IN HOURS

FIG 4·17

112(a)

(2) y_m variations: - The semi-thickness follows the general trend with lowest values around 06 hr. and maximum values around midday. It seems too that semi-thickness at Kodaikanal is greater than at Huancayo. This tendency is clear in July 1957, and November 1957, 1958, but not so in July 1958.

Variations in y_m between Q and D conditions are uncertain. In November 1957 clearly at both stations, y_m in sympathy with $h_{max}\ F_2$ is less on D days than on Q days, except for a sudden rise around 12 hours at both places. In July 1958, D values seem greater than Q at Kodaikanal, and less at Huancayo. Nothing specific can be said of July 1957 and November 1958.

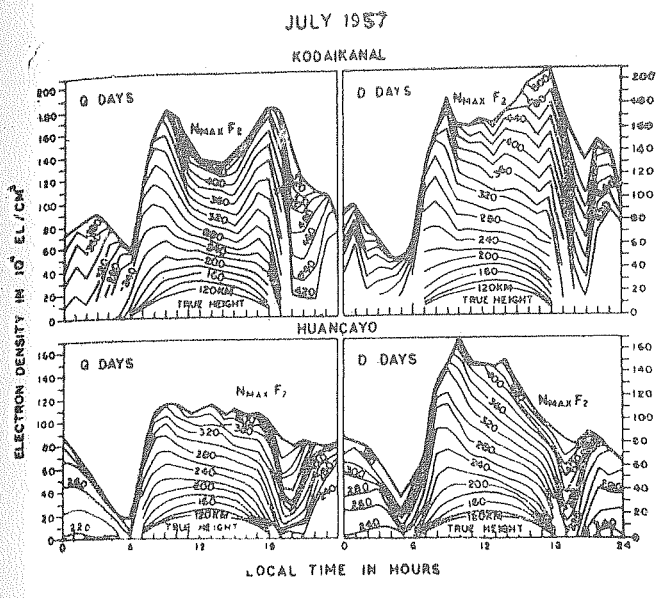
(3) N_T and $N_{max}\ F_2$ variations - follow the expected trend of minimum values around 06 hr. and maximum values in the daytime. No bite-out effect is observed in N_T. In July 1957 and July 1958, D values of both N_T and N_{max} are greater than Q values, at both stations in conformity with the accepted behaviour of disturbance effects on equatorial f_oF_2. A longitudinal difference is that the midday bite-out in $N_{max}\ F_2$ seen at Kodaikanal is not seen at Huancayo (Rastogi and Sanatani 1963). In November 1957 it is interesting to see that at both Kodaikanal and Huancayo,

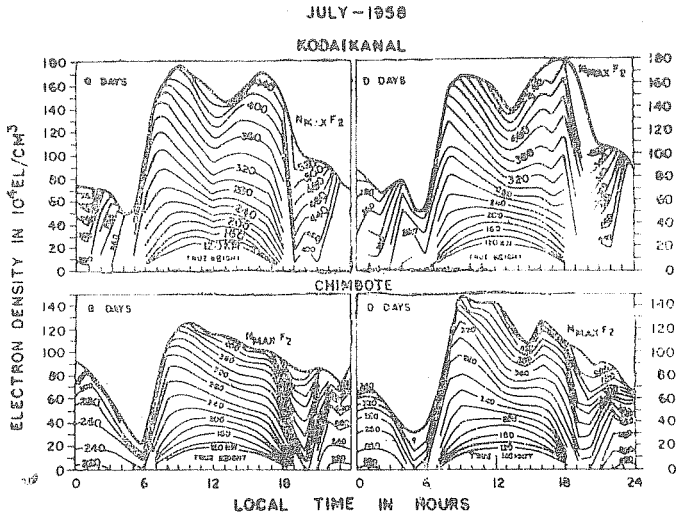
D values of $N_{max}\ F_2$ and N_T are less than Q values. This is an unusual feature for equatorial stations, and it may be recapitulated that this decrease of $N_{max}\ F_2$ during disturbed conditions also occurred at Huancayo in January 1961, and at Thumba in January 1967. One is left wondering what agent it is that occasionally in December solstitial months, destroys equatorial ionisation during disturbed conditions. In November 1958, at Kodaikanal, D values of $N_{max}\ F_2$ and N_T exceed Q values as expected; at Huancayo, however, D values continue to be less. The midday bite-out in $N_{max}\ F_2$ is absent at Huancayo in November too; at Kodaikanal it is less in November than in July.

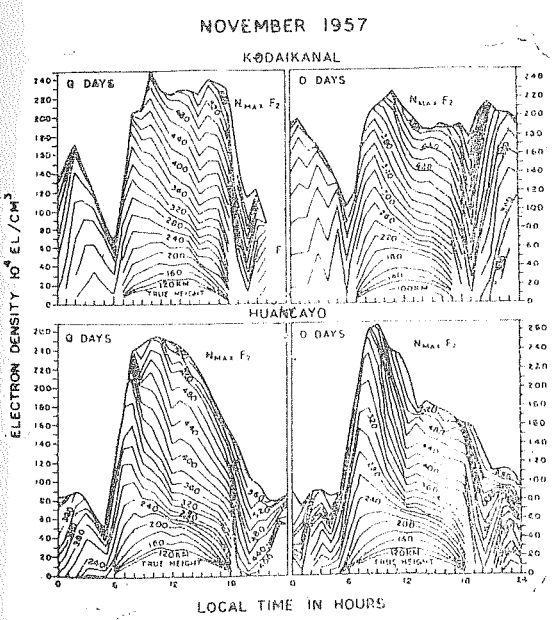
(b) Comparison of electron density distributions at constant heights.

Electron density distributions at constant heights are compared in Fig. 4.18 (Pg. 114 (a)) for Q and D days for the same solstitial months July 1957 and July 1958, and November 1957 and November 1958, at the two longitude zones. Electron densities at both Kodaikanal and Huancayo are larger in November than in July. The midday bite-out feature is totally absent at Huancayo, while at Kodaikanal, it is more pronounced in July, 1957, 1958,less in November 1957, and least in November 1958. Electron densities are larger on D days than on Q days; this however is not so at equatorial Chimbote (taken instead of Huancayo) in

114 (a)


JULY 1957
KODAIKANAL
Q DAYS
D DAYS
HUANCAYO
ELECTRON DENSITY IN 10⁴ EL/CM³
LOCAL TIME IN HOURS


JULY – 1958
KODAIKANAL
CHIMBOTE
Q DAYS
D DAYS
ELECTRON DENSITY IN 10⁴EL/CM³
LOCAL TIME IN HOURS


NOVEMBER 1957
KODAIKANAL
Q DAYS
D DAYS
HUANCAYO
ELECTRON DENSITY IN 10⁴ EL/CM³
LOCAL TIME IN HOURS

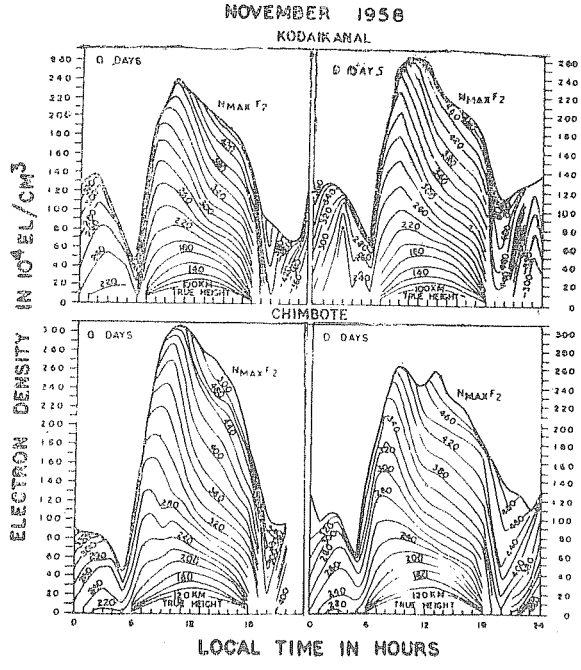

NOVEMBER 1958
KODAIKANAL
CHIMBOTE
Q DAYS
D DAYS
ELECTRON DENSITY IN 10⁴EL/CM³
LOCAL TIME IN HOURS

Fig. 4.18

November 1958, when disturbed day electron densities in the daytime are less than on quiet days. In November 1958, there is no bite-out at Kodaikanal in the midday hours, and the variations greatly resemble those of Chimbote in the American zone.

4.9 Conclusions

These studies of Quiet and Disturbed electron density distributions at true heights for different seasons and sunspot epochs for equatorial stations, bring out the following points.

(1) In general there is a tendency for both N_{max} F_2 and N_T to increase during disturbed conditions as compared to quiet, particularly in low sunspot years. Since both the parameters increase simultaneously, the peak in F_2 ionisation is not a consequence of mere height-changes, but represents a real absolute increase in the total number of electrons during disturbances. Such an increase can be caused by the following possibilities

(1) a decrease in the loss rate of ionisation

(2) an input of ionisation from elsewhere, other latitudes by thermospheric winds, or from the magnetosphere by precipitation. Recent satellite studies have proclaimed the presence of soft particle ionisation at equatorial latitudes

(Heikkila 1971; Hilton et al., 1964). Mariani (1964) feels that corpuscular radiation plays an important role in the formation of the F_2 geomagnetic anomaly.

(3) a decrease in the amount of ionisation transported out from equatorial regions to the anomaly crest region. Either the diffusion coefficients associated with the transport of plasma change, or the amount of ionisation made available for easy diffusion at greater heights changes. The latter would be governed by the equatorial $\vec{E} \times \vec{B}$ lifting force, and this could be reduced by a decrease in $\vec{E}$ during disturbed conditions. This is treated in detail in Ch. 6.

Occasionally, particularly in the December solstitial months of high sunspot years, both $N_{max}\ F_2$ and N_T decrease in the daytime during disturbed conditions as compared to quiet. This is seen at Thumba in January 1967, Huancayo in January 1961, Kodaikanal and Huancayo in November 1957, and at Huancayo again in November 1958. The decrease of f_oF_2 during disturbed conditions as compared to quiet was shown to occur at Huancayo during the December solstitial months of every year from 1957 to 1961 (Rastogi and Rajaram 1965). Since both N_T and $N_{max}\ F_2$ change, there is an actual loss in the total amount of ionisation. At such times, $h_{max}\ F_2$ varies sympathetically, with smaller daytime heights during disturbances; this suggests the presence of some force

driving ionisation down into regions of greater loss. Why it should occur only in December solstitial months is not clear. $y_m F_2$ does not show a decrease during disturbed conditions at such times.

Bhargava and Gopala Rao (1959) have classified F_2 region ionospheric storms at Kodaikanal into the positive and negative categories; they find positive storms generally commence in the evening hours. A study of F_2 layer ionisation at Kodaikanal during Quiet and Disturbed days was made by Venugopal (1959).

(3) Changes in $h_{max} F_2$ and y_m

$h_{max} F_2$ during disturbed conditions is greater than during quiet conditions for normal conditions when $N_{max} F_2$ also increases in the daytime on D days. The change is not uniform over the different hours of the day or over the different seasons, and can vary from 10 km. to 50 km. In general $h_{max} F_2$ variations are sympathetic with $N_{max} F_2$, increasing when the latter increases, and decreasing when it decreases.

$y_m F_2$ does not always exhibit this sympathetic variation with $h_{max} F_2$ and $N_{max} F_2$. Its behaviour is quite complicated and requires more study.

(4) Regarding longitudinal differences, equatorial $h_{max}F_2$ is larger in the Indian zone than in the American zone in the high sunspot years; this is fairly true of y_m too. The post-sunset rise in h_{max} F_2 is less on D days than on Q days in both zones, and on Q days, is more pronounced in the Indian zone than in the American zone. These features are clearly connected with the different geomagnetic field values at the two locations.

CHAPTER - V

LATITUDINAL VARIATION OF DISTURBED f_oF_2 PARAMETERS

5.1 Introduction

The storm-time variations of f_oF_2 and the diurnal variation of f_oF_2 on magnetically quiet and disturbed days at selected stations situated at different latitudes, and their seasonal and time variations have been discussed in Chapter 4. Here the exact degree of disturbance in f_oF_2 with latitude is obtained, by plotting certain parameters of the F-region with latitude, for individual stations ranging from 89^oN dip to 83^oS dip. Points on the plot are obtained for the entire latitude range, and as they are closely separated in dip, a fairly smooth curve can be drawn through them to indicate the exact amount of F_2 disturbance at different latitudes. No attempt has been made to fit a curve to the points; the curve drawn is by eye-approximation, and suggests the nature of changes in F_2 disturbance with latitude. The parameters chosen are (1)D_n (f_oF_2), (2) D/Q (f_oF_2) and (3)(D-Q)f_oF_2; their significance in detail and what they indicate is discussed in the sections which follow. Some of these longitudinal differences in F_2 region storm behaviour were presented at the STP Symposium held at Leningrad May 1970 (Rastogi and Rajaram 1970). Aspects of the latitudinal variation of storm-time parameters and their implications were discussed at the Symposium of Ionospheric Storms held in Japan in 1953 (Rep. of Ionos. Res. in Japan 1954).

Two significant anomalies of the F-region - the seasonal anomaly and the geomagnetic anomaly - and their variation on Quiet and Disturbed days are shown in detail. Their development with time, their longitudinal differences, and their seasonal and solar cycle variations are discussed.

5.2 Latitudinal variation of D_m (f_oF_2)

The parameter D_m (f_oF_2) implies the average value of the ratio, storm-time (f_oF_2)/corresponding median f_oF_2, for the first 48 hours of the magnetic storm. Only intense storms of the IGY-IGC period with Ap $>$ 50 on any one of the 3 days following the storm-commencement have been considered. This quantity D_m (f_oF_2) was computed season-wise, for each of about 60 stations covering almost the complete dip range from north to south; the East (Australasian) and West (American) zones were considered separately.

(a) Longitudinal differences

These D_m (f_oF_2) variations are shown in Fig. 5.1 (Pg. 121 (a)). The abscissa shows magnetic dip in degrees north and south, and the ordinate shows value of D_m (f_oF_2), from which the percentage change in f_oF_2 due to storms can be directly seen. The points represent the value of D_m (f_oF_2) for individual stations with the indicated dip values. The longitudinal comparisons of D_m (f_oF_2) between the East and West zone can be seen for the different seasons. The main features are:-

(1) In the E-months, the curve is symmetrical about the dip equator. D_m (f_oF_2) is positive between $\pm$ 30° dip suggesting that magnetic disturbances within the Appleton anomaly region increase f_oF_2. At 30° dip (the anomaly crests) in either hemisphere f_oF_2 is unaltered; beyond this the negative influence of magnetic disturbances increases with greater dip. It may be noted that the lowest values of D_m (f_oF_2) are attained at the high-latitude stations of the north in the West zone and the south in the East zone;

(2) In the D-months (December solstitial months) the symmetry observed in the E-months is lost, there being an enhanced peak of D_m (f_oF_2) centred around 45°-55° dip in the winter hemisphere (northern hemisphere). This 'hump' is slightly more intense in the West zone than in the East zone. The West zone hump drops to unity across the

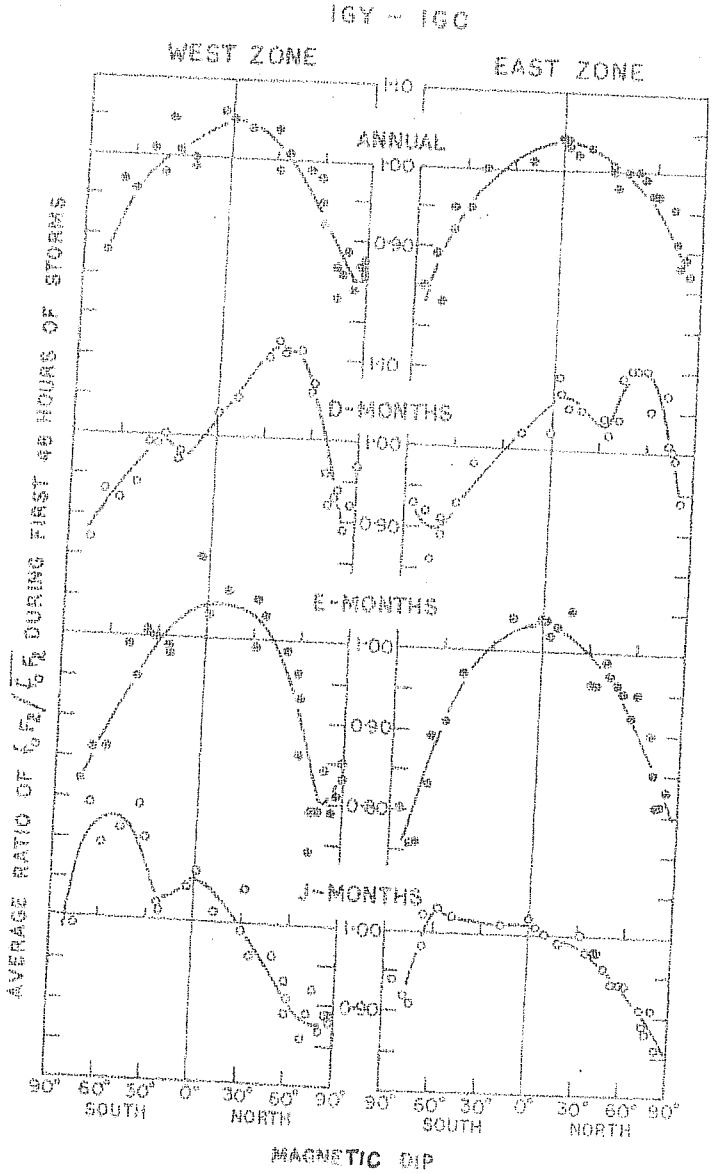

IGY ~ IGC
WEST ZONE
EAST ZONE
ANNUAL
D-MONTHS
E-MONTHS
J-MONTHS
1·10
1·00
0·90
0·80
AVERAGE RATIO OF $f_0F_2/\overline{f_0F_2}$ DURING FIRST 48 HOURS OF STORMS
90° 60° 30° 0° 30° 60° 90°
SOUTH
NORTH
MAGNETIC DIP

Fig 5·1

equator, but in the East zone, there is a dip around 30°N from where D_m (f_oF_2) rises to form another peak centred around the equator. At the highest winter latitudes in both zones, D_m (f_oF_2) drops below 1.00. In the southern summer hemisphere, in both zones D_m (f_oF_2) gradually falls off lower than 1.00 beyond 30° dip, and reaches its lowest values at the highest latitudes. The winter mid-latitude hump shows an increase of 10% in f_oF_2 during disturbed conditions, while the equatorial increase at the same time is of less magnitude.

(3) In the J-months (June solstitial months), the mid-latitude hump is again seen in the winter hemisphere (southern hemisphere). In the West zone it is centred around 60° dip, and shows a peak increase of over 10% in disturbed f_oF_2. In the East zone, the magnitude and position of the hump are indeterminate for lack of an operating station in the IGY-IGC period between 18°S dip and 48°S dip. While the West zone shows a second hump about the equator, this is not seen in the East zone. In both zones, D_m (f_oF_2) falls off below 1.00 beyond 30°N dip. The resemblance of the West zone J-month curve to the East zone D-month curve is that of a mirror image. Another longitudinal difference is that at the southern high-latitude stations in the East zone, D_m (f_oF_2) values fall below 1.00 beyond 60°S dip reaching 0.90 at the highest latitudes. In the West zone,

even the highest latitude of 75°S shows D_m (f_oF_2) of almost 1.00 in J-months.

(4) The annual average variation of $D_m(f_oF_2)$ is shown in the first set of curves. In many respects it resembles the variation seen in the E-months, being symmetrical about the dip equator.

(b) The conclusions from this are, that the behaviour of storm-time f_oF_2 differs greatly with season, and there are longitudinal differences in the intensity of this storm-time F_2 variation. The peak effect on F_2 during storms is at the winter mid-latitudes, the increase in f_oF_2 here being 10% as against only 5% increase at the equator even during the equinoxes. There is something about the West zone in the J-months which resembles the East zone in the D-months. The percentage change in disturbed f_oF_2 during magnetic storms was plotted as a function of latitude by Sinno(1954), and a similar phase change from summer to winter was pointed out.

Latitudinal variations of D/Q (f_oF_2)

The preceding section showed the occurrence of a pronounced peak in F_2 ionisation in the winter mid-latitudes. The analysis could not say anything about the local-time variations of this winter hump as it was based on universal time i.e. storm-time. In order to understand the

time -variations, it was decided to study the disturbance effects in F_2 based on International Quiet (Q) and Disturbed (D) days.

5.3 Longitudinal differences in D/Q (f_oF_2)

The mean value of f_oF_2 for the Q days for the midday hours (10-14) and midnight hours (22-02) were computed separately for each station, for the D, E and J months for the period 1957 - 1959. There were 4 months per year in each group for 3 years, thereby giving 60 quiet days. The average value of f_oF_2 for these Quiet days, Q (f_oF_2), was obtained separately for the midday and midnight hours of each of the 3 seasons. The average value of f_oF_2 for Disturbed days was computed similarly and denoted by D(f_oF_2). The ratio D (f_oF_2)/Q (f_oF_2) gives the ratio by which magnetic disturbances increase f_oF_2 values, and the variation of this ratio with latitude is shown in Fig. 5.2 (Pg. 126 (a)) for the midday and midnight hours, for each season, and for the East and West zones separately. The shaded portions indicate regions where D/Q (f_oF_2) is positive (i.e. greater than 1.00); this implies that disturbances increase f_oF_2 in these regions. The regions where the ratio is negative (i.e. less than 1.00) are the areas where disturbances decrease f_oF_2 . Below each D/Q (f_oF_2) curve is shown the corresponding average f_oF_2 variation with latitude; this depicts the normal

geomagnetic anomaly in f_oF_2 for the corresponding zone, time, and season.

(a) Midday hours.

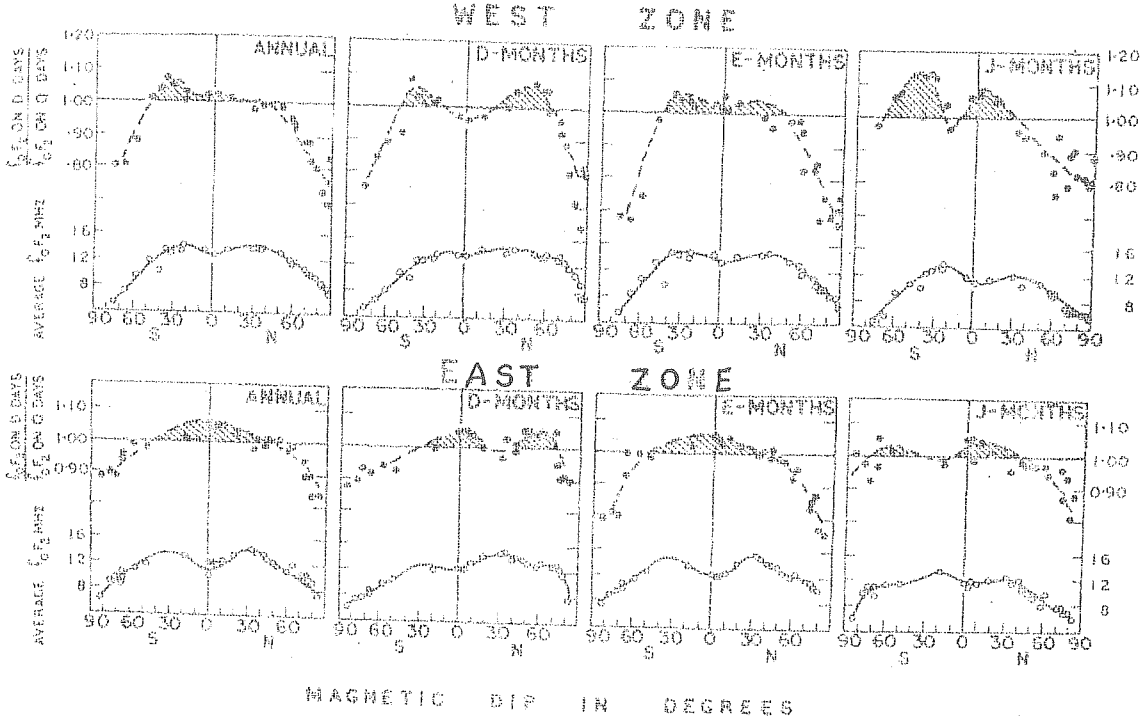
Consider the D-months - In both West and East zones, there is a positive hump of D/Q (f_oF_2) in the northern (winter) hemisphere, between 20°N dip and 65°N dip with the peak centred around 50°N dip. Beyond 50°N dip the ratio becomes negative, falling off to smaller values in the West zone than in the East zone. In the East zone, there is an equatorial positive in D/Q (f_oF_2) between ± 20° dip with a drop around 30°N dip, and the ratio falling off to less than 1.00 beyond 30°S dip. In the West zone however, there is a decrease in D/Q (f_oF_2) at the equator. This is an unusual feature for the equator, where disturbances are always believed to increase f_oF_2 and has been discussed in Ch. 4. In the southern hemisphere of the West zone, there is a positive hump between 20°S and 50°S dip. Beyond 50°S dip, the ratio becomes less than 1.00, with 0.75 at the highest southern latitudes. This graph suggests that there has been some tremendous lifting force during disturbed conditions at the equator in the West zone in the D-months, which has removed equatorial ionisation and dumped it north and south around 40° dip.

In the E-months, the D/Q (f_oF_2) variation shows a positive at all latitudes between $\pm$ 50° dip. There is a suggestion of a slight drop in the West zone about the dip equator, but it is not marked. Beyond 50° dip north and south the ratio falls off below 1.00, attaining lowest values at the high-latitudes. The region of enhanced D/Q(f_oF_2) extends slightly beyond the anomaly crests of the average f_oF_2 curves.

In the J-months, the D/Q (f_oF_2) variation in the West zone shows a hump between 20°S dip and 75°S dip with its peak around 40°S dip. After a drop around 20°S dip, there is a positive centred about the dip equator, and the values of D/Q (f_oF_2) fall off below 1.00 beyond 40°N dip. The mirror image likeness of this curve to the D/Q (f_oF_2) curve for the East zone in the D-months is readily seen. In the East zone, there is a positive hump in the southern (winter) hemisphere though its intensity seems less than in the West zone, and its magnitude indeterminate because of the absence of an operating station between 20°S dip and 50°S dip. There seems to be a slight drop around 10°S dip, then a positive hump extending from near the equator to 50°N dip; beyond that the ratio falls off below 1.00.

The Annual average variation of D/Q (f_oF_2)in the two zones resembles the E-month variation of the same parameter in the respective zones. Seasonal effects add

IGY–IGC MIDDAY HOURS (10–14)



IGY–IGC MIDNIGHT HOURS (22–02)

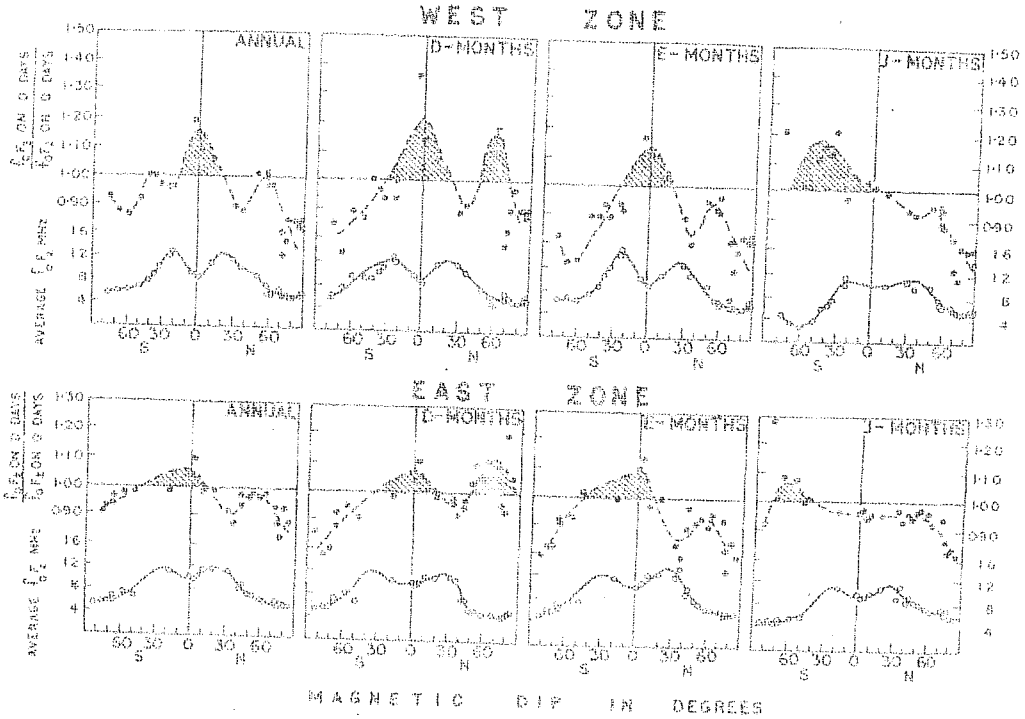


FIG 5·2

up to give the annual average variation. The average f_oF_2 variation clearly shows that the normal anomaly trough is deeper and the crests sharper in the East zone than in the West zone.

(b) Midnight hours

The D/Q (f_oF_2) variations in the midnight hours (10-14) differ greatly from the behaviour in the daytime hours.

In the D-months, in the West zone, a sharp intense hump with a peak value of 1.20 fills up the daytime equatorial drop in D/Q (f_oF_2) seen in the daytime; it exists within $\pm 30^\circ$ dip. In the southern hemisphere, beyond 30°S dip the ratio drops gradually below 1.00 . In the northern hemisphere, there is a drop around 40°N, then a sharp positive hump of D/Q (f_oF_2) covering the dip region between 45°N dip and 70°N dip; beyond 70°N dip the ratio falls off below 1.00. In the East zone, the variation is similar to that in the West zone, except that the equatorial hump is broader and lower, and the winter hump extends from 45°N dip to 90°N dip. The drop around 40°N dip is repeated here, and beyond 40°S dip the ratio falls off below 1.00. The equatorial humps in D/Q f_oF_2 seem to coincide exactly with the anomaly trough in the average $f_oF_2$curve .

In the E-months, there is an equatorial hump in both zones, with the ratio falling below 1.00 beyond 30°S dip. In the northern hemisphere, beyond 20°N dip, the ratio decreases below 1.00 in both zones, with a suggestion of humps centered around 55°N dip albeit the value is less than 1.00. The equatorial hump in D/Q f_oF_2 seems to fill up the anomaly trough in average f_oF_2 .

In the J-months, in both zones, there is a hump in D/Q (f_oF_2) in the southern (winter) hemisphere. There is no marked equatorial increase in D/Q (f_oF_2) — in fact, in the East zone, there is actually a decrease — and in the entire northern hemisphere in both zones, there is a decrease below 1.00.

The Annual average variations of D/Q (f_oF_2) bring out the equatorial positive, which fills in the anomaly trough in average f_oF_2 . Though negative values of D/Q f_oF_2 exist beyond 20° dip north and south in both zones, slight humps are seen centred around 50^oN dip.

(c) Conclusions

The intensity of disturbance effects in f_oF_2 - both increase and decrease-seems more in the West zone than in the East zone. The positive increase in ratio D/Q (f_oF_2) is larger by night than by day.

In the midnight hours, the pattern of D/Q (f_oF_2) variation with latitude is similar in the two zones, irrespective of season. The daytime pattern of D/Q (f_oF_2) differs considerably between the two zones, notably in the December solstices. The chief factors in the daytime which could cause longitudinal differences are (1) the equatorial electrojet intensity, (2) the neutral thermospheric wind

systems. The equatorial electrojet intensity would affect the vertical $\vec{E} \times \vec{B}$ drift over the equator, and the diffusion of electrons to mid-latitude regions; it would control the dip regions within 30° dip north and south. Differences in electrojet intensity in the two zones would cause modifications in the F_2 disturbance effects in this low-latitude region only in the daytime. Since little or no electrojet exists in the night-time hours, no difference would be seen.

Thermospheric winds in the two zones could have different effects in the daytime depending on the gradient in magnetic dip from the equator to the poles. The exact modifications which these winds would cause in the two zones is not too clear.

Both D_m (f_oF_2) variations, and D/Q (f_oF_2) variations in the midday hours show that the West zone in the J-months behaves like the East zone in the D-months, setting apart small differences in F_2 disturbance intensity. The D/Q (f_oF_2) variation at night does not show any such similarity.

5.4 Solar cycle variations in D/Q (f_oF_2) and average f_oF_2

These solar cycle variations are studied by comparing the East zone during high sunspot (1957-1959) and low sunspot (1963-1965), and are shown in Fig.5.3 (Pg. 130 (a)) for both midday and midnight hours.

(a) Midday hours

The detailed variation of D/Q (f_oF_2) for the IGY-IGC period has been described in Section 5.3. The chief difference which the low sunspot years (1963-1965) show, is that a greater range of latitudes experience ratios of D/Q (f_oF_2) larger than 1.00. Stations between $\pm$ 80° dip experience D/Q (f_oF_2) larger than 1.00 i.e. disturbances increase f_oF_2 here, only locations with dip greater than 80° (notably those in the southern hemisphere) experience values of D/Q (f_oF_2) less than 1.00 i.e. disturbances decrease f_oF_2 here. In all three seasons, D,E, and J months, equatorial positive D/Q (f_oF_2) is seen in the low sunspot years as in the high, and the magnitude is as large if not more. Whereas the mid-latitude hump in D/Q (f_oF_2) was confined only to the winter hemisphere in IGY-IGC, mid-latitude humps seem to occur in both hemispheres in all seasons of the low sunspot years, though here too the winter hump is more pronounced. Slight drop in the D/Q (f_oF_2) values are seen at $\pm$ 30° dip in all seasons, and the overall variation pattern is alike for all the month-groups.

The average f_oF_2 curves show absence of the 70° winter spur, and lower f_oF_2 values at all latitudes in the low sunspot years.

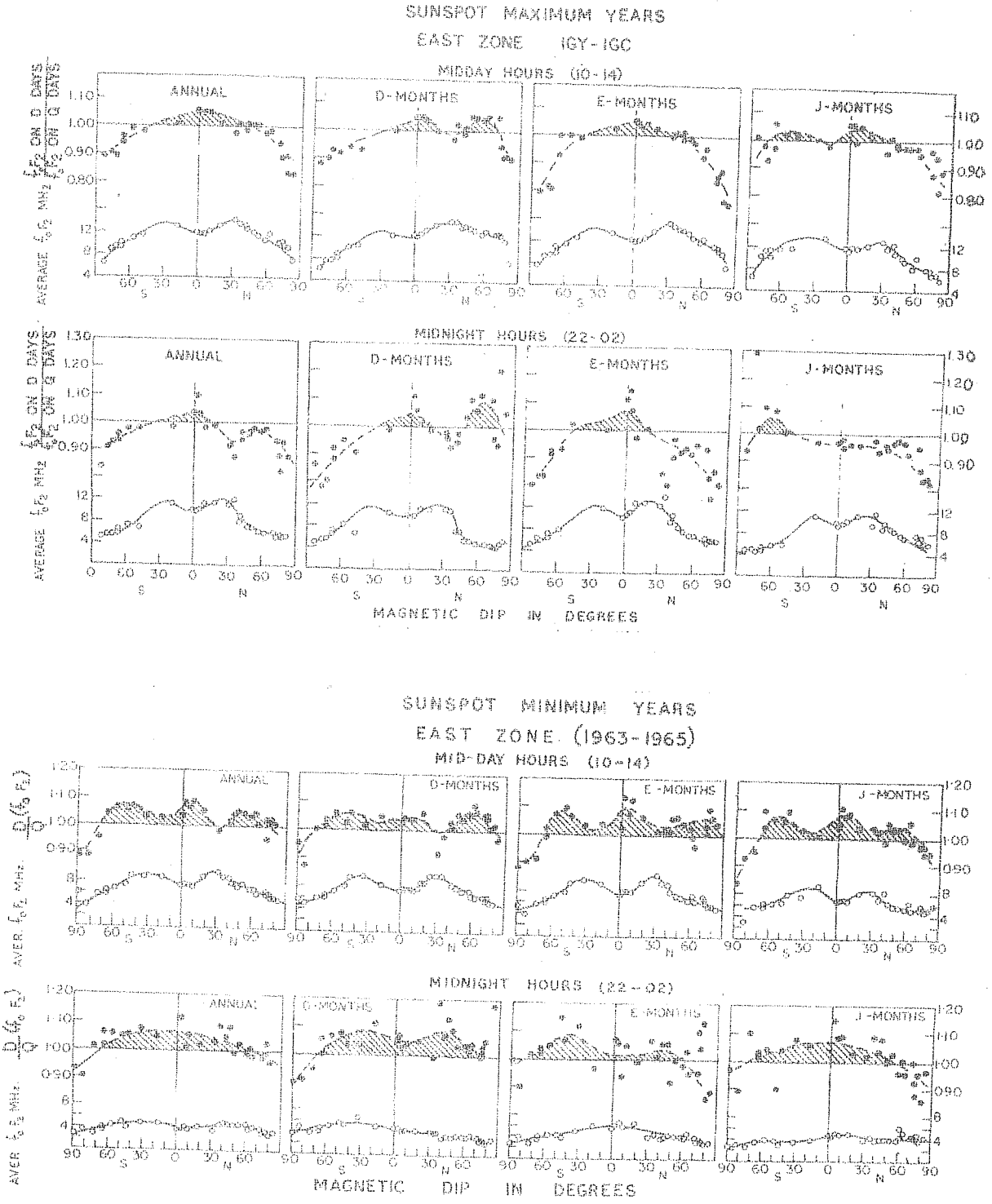

SUNSPOT MAXIMUM YEARS
EAST ZONE IGY-IGC
MIDDAY HOURS (10-14)
ANNUAL
D-MONTHS
E-MONTHS
J-MONTHS
MIDNIGHT HOURS (22-02)
MAGNETIC DIP IN DEGREES
SUNSPOT MINIMUM YEARS
EAST ZONE (1963-1965)
MID-DAY HOURS (10-14)
MIDNIGHT HOURS (22-02)
MAGNETIC DIP IN DEGREES

Fig 5·3

(b) Midnight hours

There is a large scatter of points in the night-time variation of D/Q (f_oF_2) for the low sunspot; this may be due to the average f_oF_2 itself being as low as 2-6 MHz. This night-time scatter is not so much in the high sunspot years, probably because the average f_oF_2 itself is higher, lying between 6-12 MHz.

The D/Q (f_oF_2) variation for the low sunspot years does not greatly differ between the D, E, and J months. Once again almost all locations between $\pm$ 70° experience positive ratios i.e. f_oF_2 increases with disturbances; only beyond are negative ratios seen. In this respect, it greatly differs from the high sunspot years which show the greater range of latitudes to experience decreased f_oF_2 during disturbances. The night-time average f_oF_2 curves shows a flat latitudinal variation in low sunspot; the anomaly shows up clearly even at night in high sunspot years.

(c) Conclusions

To summarise the main results:

(1) In low sunspot years, a very large range of latitudes extending from low to high latitudes experience increased f_oF_2 during disturbances both by day and by night.

This goes against the classical belief in which magnetic storms are supposed to cause an increase of f_oF_2 in winter and a decrease of f_oF_2 in summer at middle latitudes. The curves in Fig. 5.3 show no seasonal change-over at the middle latitudes. Even the highest latitudes which classically are believed to experience decreased f_oF_2 during disturbances in all seasons, show positive D/Q (f_oF_2) in winter and equinox.

(2) <u>In high sunspot years</u> the range of latitudes experiencing positive D/Q (f_oF_2) is far less. The behaviour fairly conforms to the classical beliefs, except for a pronounced hump at the winter mid-latitudes, larger than the equatorial enhancement.

(3) <u>Both sunspot years</u> show slight decrease in D/Q (f_oF_2) around $\pm$ 30° dip. (i.e. at the anomaly crests). This could be significant and is most probably connected with a weakening of the equatorial $\vec{E} \times \vec{B}$ uplift during disturbances. It is dealt with in detail in Ch. 6.

The factors which vary greatly between high and low sunspot years are the atmospheric temperatures and charged particle energies. Both these are greater in high sunspot than in low, and could be the factors responsible for the differences observed in disturbed f_oF_2 behaviour. They are treated in detail in Chapter 7.

5.5 Time-variations of (SD f_oF_2)

The variation of F_2 region disturbance has also been studied by considering the SD (f_oF_2) variation i.e. the [(Disturbed f_oF_2) - (Quiet f_oF_2)] variation. SD (f_oF_2) was computed for each station for each hour of the D, E, and J months of the IGY-IGC period. The stationswere then grouped into different dip zones, stations having similar SD (f_oF_2) behaviour falling into a zone. The entire latitude range from north to south is covered in ten dip zones, and the SD (f_oF_2) behaviour for each hour of the day is shown for the different seasons, for each of the ten zones.

(a) Longitudinal variations in SD(f_oF_2) for high sunspot

The longitudinal variation in SD (f_oF_2) for the IGY-IGC period has been shown by comparing the West zone and the East zone as shown in the first two blocks of Fig. 5.4 (Pg. 134 (a))

The Annual average as well as the variations for the D, E, and J months are shown. Increase in f_oF_2 during disturbances is depicted by shading. The features in either zone are -

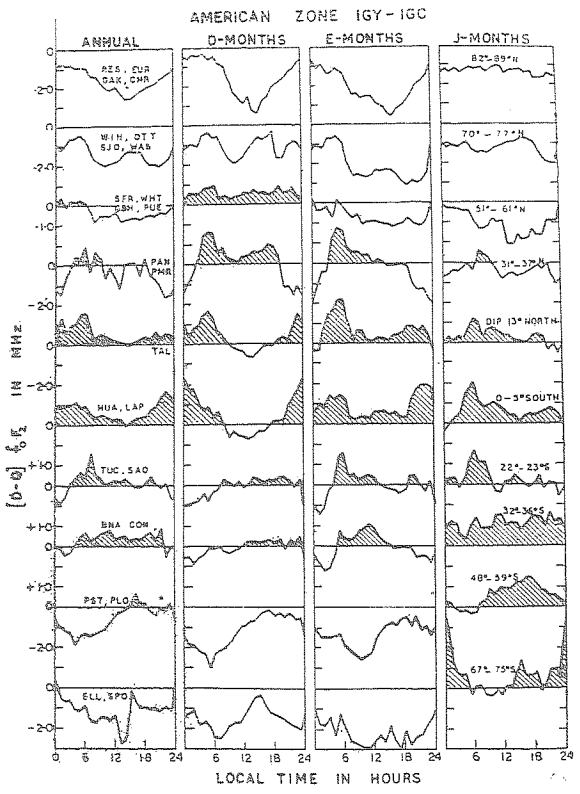
(1) Equatorial stations generally show enhanced f_oF_2 during disturbances in all seasons (an exception is the West zone in the D-months). The largest enhancement is in

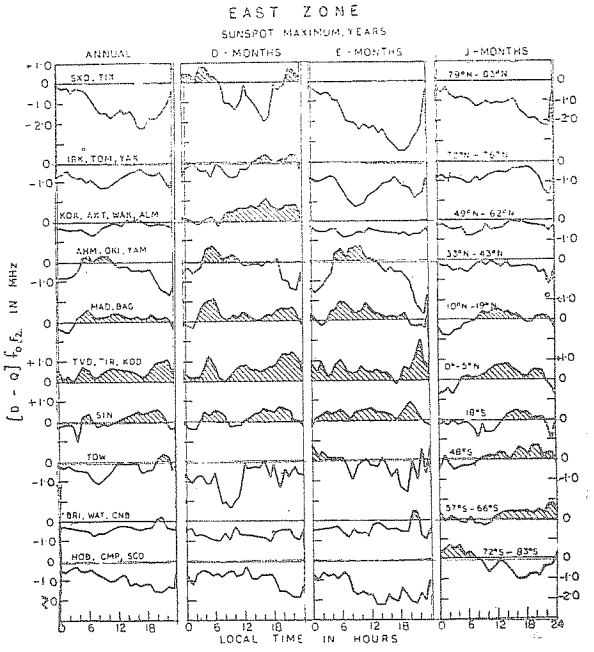
the night-time hours with peaks before dawn and after dusk. In the daytime, (D-Q) f_oF_2 is smaller and the peaks approach together with increasing latitude to merge at around 50° — 60° dip. This is particularly true of the D-months.

2) The E-month and Annual Average behaviour are similar with positive (D-Q) f_oF_2 at all hours till $\pm$ 30° dip and a decrease beyond in both hemispheres. The decrease in (D-Q) f_oF_2 becomes larger with increasing latitude, and the time of maximum decrease shifts from morning to the sunset hours.

(3) In the winter hemisphere, the positive phase of (D-Q) f_oF_2 exists till even the highest latitudes. In the summer hemisphere, a decrease commences at relatively low latitudes, with the magnitude increasing steadily to the highest latitudes, and the largest values occurring in the night hours

Several similarities and differences are seen in the (D-Q) f_oF_2 behaviour between the two longitude zones. The change in value of D(f_oF_2) as compared to Q (f_oF_2) is on the whole more in the American zone than in the East zone at all latitudes. The largest differences are seen in the D-months. In the West zone, equatorial stations show SD(f_oF_2) to be less than 1.00 in the midday hours, and this pronounced midday drop is seen up to the dip zone 31^oN - 37^oN . Beyond this at 51^oN - 61^oN dip, a single positive peak of D/Q f_oF_2 is formed. In the East zone, (D-Q) f_oF_2 values are smaller around midday hours but they are never negative. Here too the drop at midday continues upto the dip zone 33^oN - 43^oN and also at 18^oS. In the West zone, peak (D-Q) f_oF_2 occurs at the midnight hours at the equator, but these peaks approach closer together as one goes north. In the East zone peak values are centred around dawn and dusk.


AMERICAN ZONE IGY-IGC
ANNUAL
D-MONTHS
E-MONTHS
J-MONTHS
RES, EUR
OAK, CMR
WIH, OTT
SJO, WAB
SFR, WHT
FBM, PUE
PAN
PMR
TAL
HUA, LAP
TUC, SAO
BNA, COM
PST, PLO
ELL, SPO
82°-89°N
70°-77°N
51°-61°N
31°-37°N
DIP 13° NORTH
0-3° SOUTH
22°-23°S
32°-36°S
48°-59°S
67°-75°S
[D-Q] fₒF₂ IN MHz
LOCAL TIME IN HOURS


EAST ZONE
SUNSPOT MAXIMUM YEARS
ANNUAL
D-MONTHS
E-MONTHS
J-MONTHS
SKD, TIK
IRK, TOM, YAK
KOK, AKT, WAK, ALM
AHM, OKI, YAM
MAD, BAG
TVD, TIR, KOD
SIN
TOW
BRI, WAT, CNB
HOB, CMP, SCO
79°N-83°N
72°N-76°N
49°N-62°N
33°N-43°N
10°N-19°N
0°-5°N
18°S
48°S
57°S-66°S
72°S-83°S
[D-Q] fₒF₂ IN MHz
LOCAL TIME IN HOURS

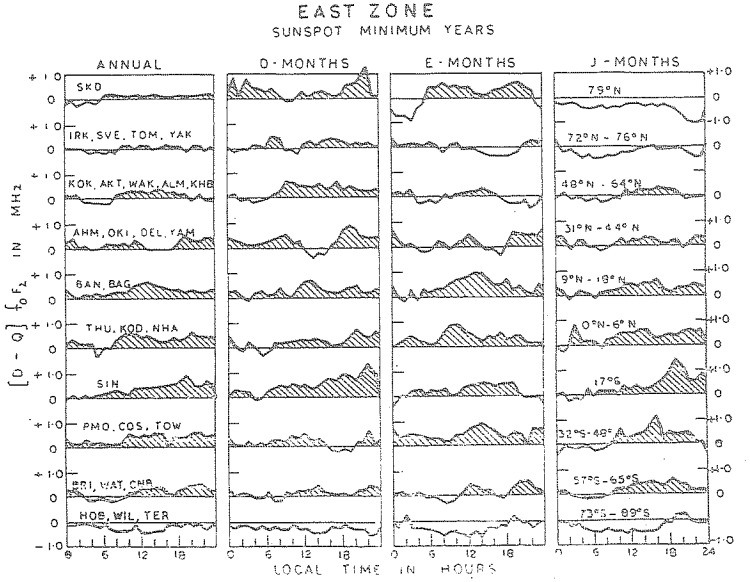

EAST ZONE
SUNSPOT MINIMUM YEARS
ANNUAL
D-MONTHS
E-MONTHS
J-MONTHS
SKD
IRK, SVE, TOM, YAK
KOK, AKT, WAK, ALM, KHB
AHM, OKI, DEL, YAM
BAN, BAG
THU, KOD, NHA
SIN
PMO, COS, TOW
BRI, WAT, CNB
HOB, WIL, TER
79°N
72°N-76°N
48°N-54°N
31°N-44°N
9°N-18°N
0°N-6°N
17°S
32°S-48°S
57°S-65°S
73°S-89°S
[D-Q] fₒF₂ IN MHz
LOCAL TIME IN HOURS

Fig. 5.4

It is interesting to consider the progress in time of peak (D-Q) f_oF_2 through the different latitudes. In the E-months in both zones it appears that the peak effect at high latitudes occurs around dusk hours, and progresses through midday at mid-latitudes, to the dawn-dusk hours at the equator.

In the D-months in the East zone the peak positive disturbance effect seems to progress from the night hours at the high latitudes, through daytime to the dawn-dusk hours at the equator, in the northern hemisphere. In the West zone it seems to progress from the midday hours at high latitudes, through dawn-dusk hours to the mid-night hours at the equator. In the southern hemisphere the peak change in (D-Q) f_oF_2 seems to progress from dawn hours at the high latitudes, to dusk hours at the equator in the West zone; in the East zone, it seems to progress from dusk hours at the high latitudes, through daytime at mid-latitudes, back to dusk hours at the equator.

In the J-months the peak positive (D-Q) f_oF_2 variation progresses in the West zone from midnight in the southern high latitudes, through daytime to dawn hours at the equator. In the East zone, it seems to progress from night through evening, to midday hours at the equator. Little can be said about the progress of the SD (f_oF_2) peak variation in the northern hemisphere for either zone.

The implications of these time-variations are not fully understood, but they may bear some relationship to the currents set up at auroral and high latitudes during disturbed conditions, and the means by which these currents close their circuits through the low latitudes, progressively carrying the disturbance with them. The observation that equatorial stations experience peak effects at the dawn-dusk hours can be related to the DS current system shown in Fig. 1.13 in Chapter 1 after Obayashi and Jacobs (1957). It may be seen that the concentration of these currents at equatorial regions is largest around the dawn-dusk hours. The mode of development of ionospheric storms with time and latitude has been studied by Obayashi (1954) and Nagata and Oguti (1953).

(b) Solar cycle variations in SD (f_oF_2)

The solar cycle variation of (D-Q) f_oF_2 is studied by comparing the ten dip zones in the East zone for the IGY-IGC period (high sunspot) and the IQSY period (low sunspot). The variations are shown in the two right-hand blocks of Fig. 5.4 (Pg. 134 (a)).

In the D-months, in the low sunspot years, some positive phase of (D-Q) f_oF_2 exists right from the equatorial region of dip 0^oN - 6^oN to the high-latitudes of 79^oN in the northern hemisphere, although the peak change

is only of the order of 1.00 MHz. In high sunspot years the peak change is often 2.0 MHz, but the positive phase is much less at latitudes above 49°N - 62°N dip. In both epochs, the peak disturbance-effect seems to progress from the night-time hours at high northern latitudes, through midday, to dawn-dusk hours at the equator. In the southern hemisphere, in low sunspot years, again some positive phase exists till 57°S - 65°S dip, and only at 73°S - 89°S is it negative at all hours. In the high sunspot years (D-Q) f_oF_2 becomes negative at all hours in all regions south of 45°S dip. The maximum change in (D-Q) f_oF_2 in the low sunspot years seems to progress from midday hours at southern high latitudes, to midnight hours at the equator.

In the southern hemisphere in low sunspot years, some positive phase of (D-Q) f_oF_2 persists right till 57°S-65°S dip; only at the region 73°S-89°S dip is a negative seen at almost all hours of the day. The peak disturbance appears to shift from the pre-noon hours at high latitudes, through afternoon hours, back to pre-noon hours at the equator. In the high sunspot period, the positive phase is seen clearly only till ± 30° dip, beyond which negative phase occurs.

J-months - In low sunspot years, in the northern hemisphere, the positive phase of (D-Q) f_oF_2 persists till about 48°N-64°N dip, and beyond that negative phase occurs. The progress is clearly from midnight hours at high latitudes, to midday

hours at the equator. In the southern hemisphere, some positive phase of (D-Q) f_oF_2 is seen till 57°S - 65°S dip; beyond this at 73°S - 89°S dip, decreased SD (f_oF_2) is seen at all hours. The progress of peak disturbance is from midday hours at high latitudes to evening hours at the equator.

Annual average - The annual average (D-Q) f_oF_2 variations suggest that in the low sunspot years some positive phase persists till the highest latitudes in the northern hemisphere, and to fairly high latitudes of 57°S - 65°S in the southern hemisphere. Only at the highest southern zone of 73°S - 89°S is a negative phase seen.

(c) Conclusions

One can say that while disturbances in the high sunspot change f_oF_2 by as much as 3.0 MHz especially at polar latitudes, in the low sunspot the peak change is much less, only of the order of 1.0 MHz.

In the low sunspot years disturbances seem to increase f_oF_2 at almost all latitudes in all seasons. Only in the 73°S - 89°S zone in the southern hemisphere is there a marked decrease of f_oF_2 in all seasons. In high sunspot years, except for some amount of winter positive in (D-Q) f_oF_2 which persists till very high latitudes, most

stations beyond 45° dip north and south suffer a decrease of f_oF_2 during disturbances during summer and equinoxes. The disturbance effects seen at the equator seem to be a combination of two sources, one travelling down from the northern high latitudes, the other travelling up from the southern high latitudes.

5.6 Diurnal development of the Latitudinal Variation of (D-Q) f_oF_2

The above section brought out the solar cycle and longitudinal differences in the daily variation of (D-Q) f_oF_2 at different dip zones. The feature (D-Q) f_oF_2 can be viewed from another angle. Instead of grouping stations into dip zones as described above, one can plot the absolute value of (D-Q) f_oF_2 in MHz for the stations studied, as a function of magnetic dip. Such plots for different hours of the day give a clear idea of the disturbance changes in f_oF_2 with time and latitude. This is done for the three seasons-Equinox, December Solstices, and June solstices in Fig. 5.5(a) (Pg. 141 (a)) . Longitudinal and solar cycle differences are again brought out by considering the West zone (high sunspot), East zone (high sunspot), and East zone (low sunspot) during each season. Shaded regions indicate excess of f_oF_2 during disturbed conditions.

Equinoxes

1. The variation in all three sets is more or less symmetrical about the dip equator as one would expect. The equatorial regions in high sunspot experience considerable enhancement at 06 hr, while the enhancement is found in low sunspot years around 12 hr. In the night hours there is a tendency for double peaks in (D-Q) f_oF_2 but most hours show a smooth symmetry about the dip equator.

December and June Solstices

There is marked asymmetry about the dip equator in the (D-Q) f_oF_2 variation. Remembering that December is northern winter and southern summer, and that June is northern summer and southern winter, one can discuss the variations in terms of local season. The progress with time of the mid-latitude winter hump in D/Q (f_oF_2) discussed in Section 5.3 can be studied by observing the time variation of D-Q (f_oF_2).

In the December solstices in high sunspot, the first suggestion of the hump in (D-Q) (f_oF_2) is around 08 hr. when it is more prominent in the West zone; its limits between + 30° dip and + 70° dip are well defined by 10 hr. Its existence even in the low sunspot is seen, though the high-latitude limit is almost 90° dip. It remains well

defined within the same dip range till 22 hr. in the East zone (high sunspot), but it broadens out earlier in the West zone (high sunspot), and the East zone (low sunspot). A prominent difference between West and East zonesis the presence of a positive (D-Q) f_oF_2 at all hours at the equator and low-latitude belt of the East zone. This is replaced by decreased (D-Q) f_oF_2 at the equator between 08 hr. and 16 hr. in the West zone,(an unusual feature which has already been referred to earlier). Also in the East zone (high sunspot) while a trough centred around 70^oS dip persists from 00 hr. to 16 hr. it is far less prominent in the East zone (low sunspot), and vanishes by 08 hr in the West zone (high sunspot).

In the June solstices, the development of the mid-latitude winter hump is less marked. In the East zone (high sunspot) it commences at 12 hr and is seen till 00 hr. In the West zone (high sunspot) a broad positive (D-Q) f_oF_2 covers the whole southern hemisphere from 12 hr to 22 hr and diminishes in intensity after 22 hr to 02 hr; between 02 hr and 10 hr it is centred about the equator. The East zone (low sunspot) also shows a broad southern peak between 10 hr and 22 hr.

Large positive values of (D-Q) f_oF_2 in the low-latitude American zone occur at 06 hr (dawn) in all seasons.

141(a)

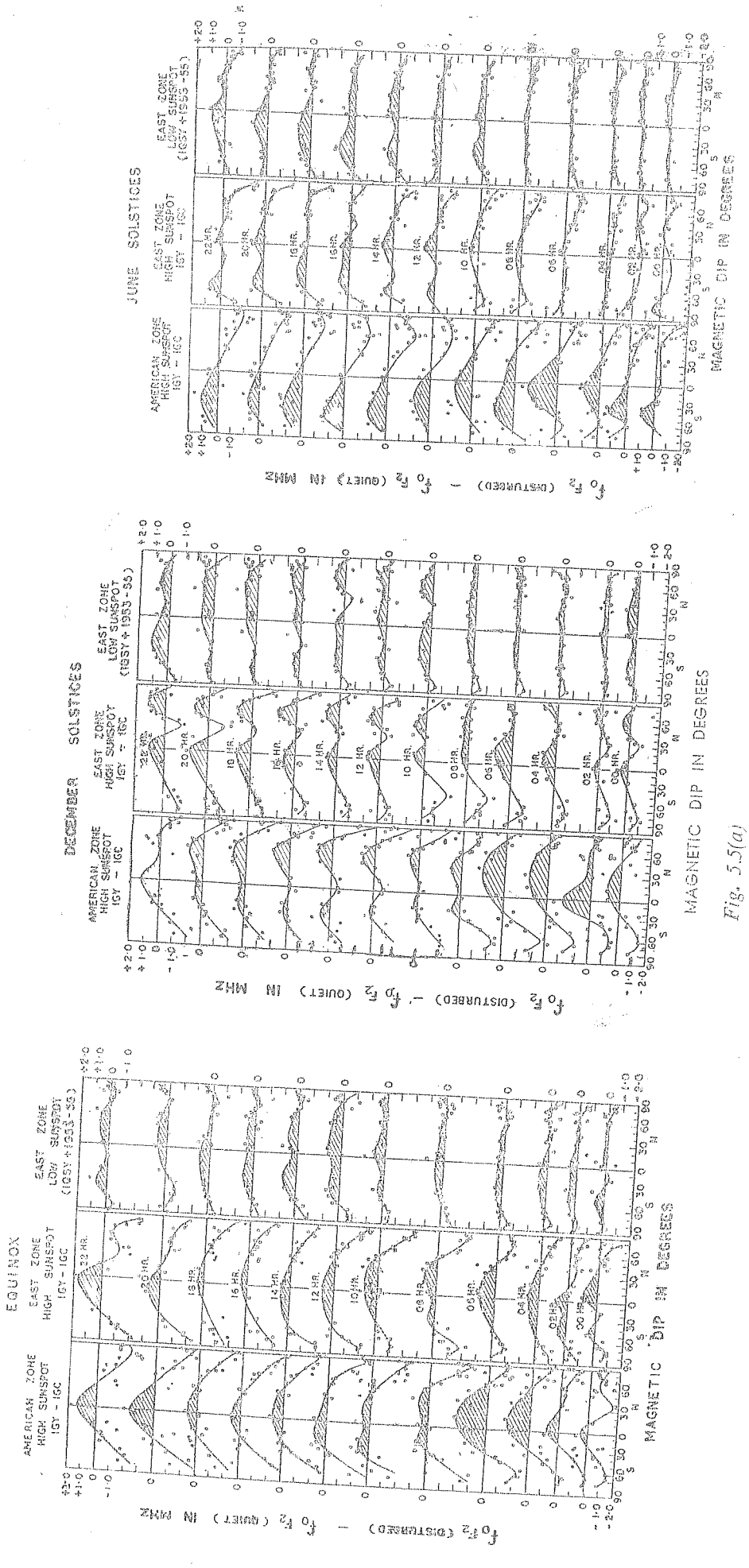

JUNE SOLSTICES
DECEMBER SOLSTICES
EQUINOX
AMERICAN ZONE HIGH SUNSPOT IGY - IGC
EAST ZONE HIGH SUNSPOT IGY - IGC
EAST ZONE LOW SUNSPOT (IGSY + 1953 - 55)
MAGNETIC DIP IN DEGREES
fo F2 (DISTURBED) − fo F2 (QUIET) IN MHZ

Fig. 5.5(a)

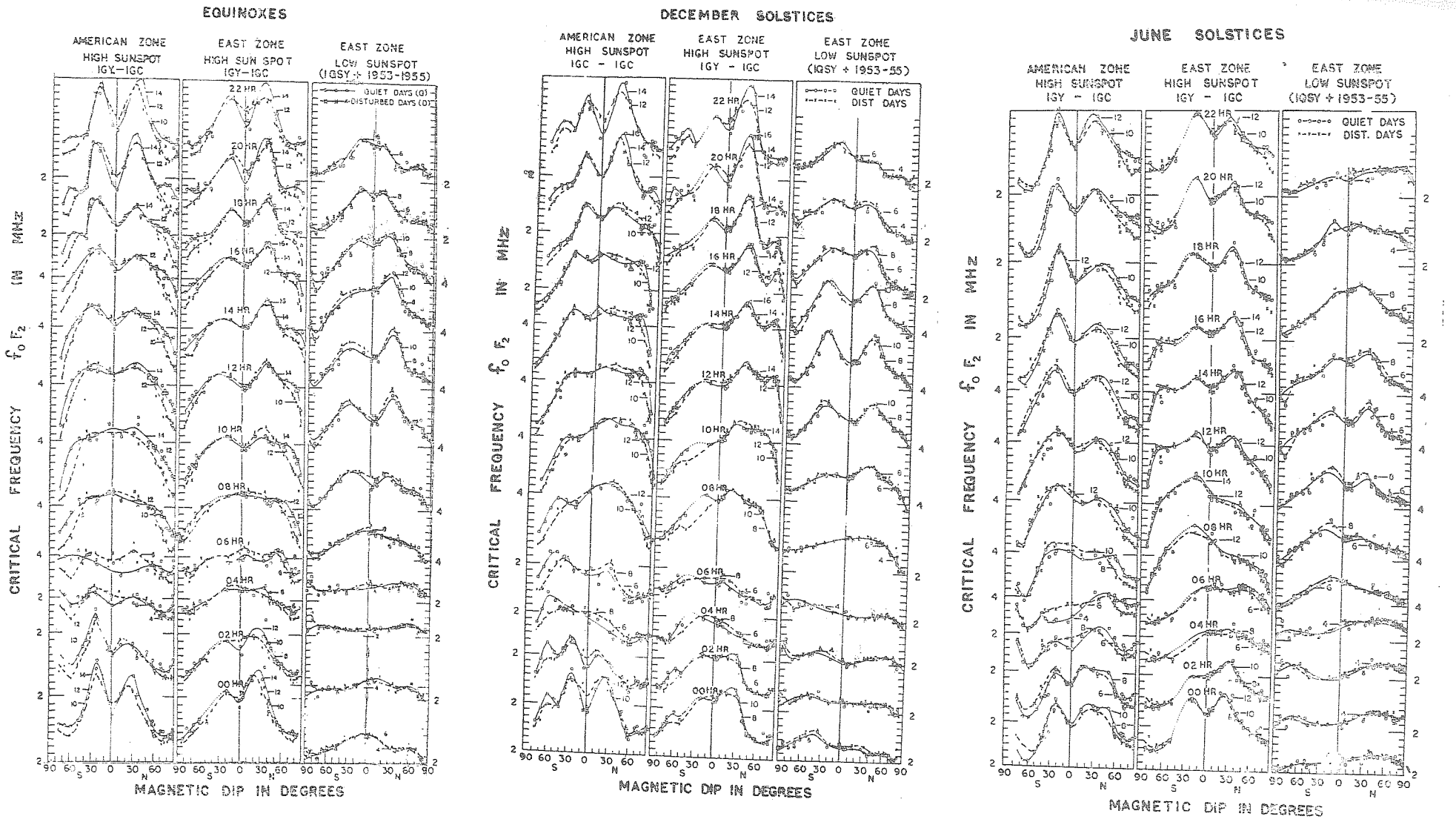

EQUINOXES
AMERICAN ZONE HIGH SUNSPOT IGY–IGC
EAST ZONE HIGH SUN SPOT IGY–IGC
EAST ZONE LOW SUNSPOT (IQSY ÷ 1953-1955)
QUIET DAYS (Q)
DISTURBED DAYS (D)
CRITICAL FREQUENCY f_0F_2 IN MHz
MAGNETIC DIP IN DEGREES
DECEMBER SOLSTICES
AMERICAN ZONE HIGH SUNSPOT IGC – IGC
EAST ZONE HIGH SUNSPOT IGY – IGC
EAST ZONE LOW SUNSPOT (IQSY ÷ 1953-55)
QUIET DAYS
DIST DAYS
JUNE SOLSTICES
AMERICAN ZONE HIGH SUNSPOT IGY – IGC
EAST ZONE HIGH SUNSPOT IGY – IGC
EAST ZONE LOW SUNSPOT (IQSY ÷ 1953-55)
QUIET DAYS
DIST. DAYS

Fig. 5.5(b)

In the East zone, this is not seen at all in the June solstices.

5.7 The Geomagnetic Anomaly on International Quiet and Disturbed Days.

The variations of (D-Q) f_oF_2 as a function of latitude discussed in Section 5.7 are derived from the curves shown in Fig. 5.5(b) (Pg. 141 (b)). The latter curves show the variation of absolute f_oF_2 with dip on magnetically Quiet(Q) and Disturbed (D) days; i.e. they show the development with time of the geomagnetic anomaly, that on D days shown by a dashed line through crosses, and that on Q days shown by a full line through circles. As before, the three seasons Equinox, December solstices, and June solstices are considered; longitudinal and solar cycle differences are brought out by taking same three sets of data, the American zone(high sunspot), East zone (high sunspot) and East zone (low sunspot).

It is interesting to study these anomaly curves in relation to the (D-Q) f_oF_2 curves for the corresponding season, shown on Page 141 (a) in Fig. 5.5 (a).

At this stage we define some terms which will be frequently used in the section which follows-

1) The hump refers to the positive enhancement in D/Q (f_oF_2) or (D-Q) f_oF_2 observed at mid-latitudes, generally in the winter hemisphere.

2) The spur refers to the enhanced f_oF_2 at 70° dip generally in the winter hemisphere in the daytime; it is seen on both Quiet and Disturbed days with differing magnitude.

3) The anomaly trough in f_oF_2 is centred about the equator; another trough is situated between the anomaly crest (about 30° dip) and the spur at 70° dip.

December Solstices

1. The East zone (high sunspot) (D-Q) f_oF_2 variations show that the equatorial positive, and mid-latitude winter hump in (D-Q) f_oF_2 occur at the exact latitudes where the f_oF_2 equatorial anomaly trough and the trough between the winter anomaly crest (30°N) and the winter spur at 70°N are located. The anomaly curves show that these latter phenomena start developing at 08 hr, and the progress of these go hand in hand with the progress of the equatorial positive and mid-latitude winter hump in (D-Q) f_oF_2. The equatorial trough, and the trough before the spur in quiet f_oF_2 do have a tendency to be smoothened out by increased

f_oF_2 values on Disturbed days. The daytime winter spur shifts over to the summer (southern) hemisphere at night, and a spur is now seen in the south around 60°S dip. Here disturbed f_oF_2 flattens down the spur by decreased f_oF_2 values, and the feature is seen as a negative hump in (D-Q) f_oF_2 in the summer side at night. This is true of both East and American zones (high sunspot).

(2) An additional feature in the American zone is that instead of the equatorial positive, negative values of (D-Q) f_oF_2 are seen in the daytime. A glance at the anomaly curves below shows that in this zone the daytime anomaly trough at the equator is completely absent on quiet days. What is more, there is a peak at the equator between 08 hr and 16 hr with a trough between this peak and the anomaly crest (30°S dip) in the south, and another trough between the equator and the winter spur (70°N dip) in the north; there is no normal anomaly crest in the north. It looks as though in this zone, the ionisation at the anomaly crest comes not from the equator, but from narrow regions on either side of an equatorial belt. This aspect is puzzling, and one wonders if it is the $(\vec{E} \times \vec{B})$ mechanism at all which is operating in the formation of the anomaly. Lockwood and Nelms (1964) from topside sounder studies observe a less pronounced geomagnetic anomaly in regions around 75° W meridian. Longitudinal effects in the F-region equatorial anomaly have been studied from ground-based observations

by Narasinga Rao (1966), but these unusual features have not been brought out.

The disturbed f_oF_2 curves for the American zone show that the equatorial peak in f_oF_2 is lowered and the trough before the northern spur is filled up, giving negative values of (D-Q) f_oF_2 at the equator, and the positive northern mid-latitude (D-Q) f_oF_2 winter hump. At all the night hours 18 to 06, the equatorial anomaly trough is present on quiet days and the (D-Q) f_oF_2 shows positive values at the equator. The formation of the summer spur on quiet days around 60^oS dip at night may be noticed. Disturbances tend to erase the night spur by decreasing f_oF_2, and cause the negative hump in (D-Q) f_oF_2 in the southern hemisphere from 00 hr. to 08 hr.

3. In low sunspot (East zone) it is difficult to correlate the development of (D-Q) f_oF_2 with the development of the anomaly, as the latter does not differ greatly between Q and D days.

June solstices

East zone

The winter spur in f_oF_2 in the southern hemisphere is clearly seen from 12 hr. to 18 hr. and is accompanied by positive (D-Q) f_oF_2 in the trough lying between the spur

and the southern anomaly crest. In addition the equatorial anomaly trough is filled up by positive (D-Q) f_oF_2. This southern June spur itself is less prominent than the northern December spur, and the same is true of the (D-Q) f_oF_2 winter mid-latitude hump.

West zone

No spur is seen in the winter hemisphere in the American zone in June, and the f_oF_2 on D days seems to be enhanced right from equator to southern high latitudes. This gives a large positive (D-Q) f_oF_2 extending over the whole southern hemisphere. In this season, the anomaly trough at the equator on quiet days is clear, but equatorial (D-Q) f_oF_2 is positive only from 04 hr. to 10 hr. with little or no change at other hours.

East zone (low sunspot)

Once again the difference in the f_oF_2 anomaly curves between disturbed and quiet days is not much, and little can be said about its relationship with (D-Q) f_oF_2.

Equinoxes

A study of the f_oF_2 anomaly curves for quiet days shows the presence of some spur effect in the northern hemisphere around 60^oN dip from 08 hr. to 20 hr. in both the East and American zones - this is seen to some extent in the

low sunspot years too in the East zone, However, there is no filling-up of the trough between the spur and the northern anomaly crest, on disturbed days; instead what happens is the levelling down of the spur by decreased values of f_oF_2 . The equatorial anomaly trough is filled up on D days. Consequently, the (D-Q) f_oF_2 variation is smooth and symmetrical about the dip equator, with positive values of (D-Q) f_oF_2 occupying the region of the anomaly trough. This is true of both zones.

Conclusions

From these observations we come once again to the feature pointed out in Section 4.2, namely that magnetic disturbances have a tendency to level out the anomalies of the F_2 region.

Here we see that:

1) They fill up the equatorial ahomaly trough. King et al., (1967) from topside sounders note too that the equatorial anomaly trough seems to get filled up during storms.
2) They level out the winter spur by either
   a) filling up the trough between the spur and the anomaly crest or
   b) by reducing the spur itself.

The mechanisms involved in (a) and (b) may arise from different causes.

Also the causes of (1) and (2) may be different, and these are dealt with in detail in Chapter 7.

5.8 The seasonal anomaly on magnetically Quiet and Disturbed days

The seasonal anomaly of the Quiet F-region has been discussed in Chapter 2.

In the following sections, comparison of the seasonal anomaly at all latitudes has been made for magnetically Quiet and Disturbed conditions, for different sunspot epochs and longitude zones, by choosing the midday hours (10-14) and the midnight hours (22-02). The equinox values are taken as unity, and the ratios December(f_oF_2)/Equinox(f_oF_2)and June (f_oF_2)/ Equinox (f_oF_2) for these hours have been plotted against magnetic dip north and south .

(a) Solar cycle variations of the seasonal anomaly

(i) Midday hours

Fig. 5.6 (Pg. 151 (a)) shows the seasonal anomaly for the East zone during midday hours, during the sunspot maximum (1957-1959) and sunspot minimum (1963-1965) periods. The top set of curves show the latitudinal variation of the

ratio December (f_oF_2)/Equinox (f_oF_2) while the lower set of curves show the variation for the ratio June (f_oF_2)/Equinox (f_oF_2) The crosses with the dashed line drawn through them show the variation for the International Disturbed days (D) ; the circles with full lines through them show the variation for the International Quiet Days (Q).

December (f_oF_2) / Equinox(f_oF_2) ratio.

In sunspot maximum the ratio is less than 1.00 in the entire southern (summer) hemisphere, the magnitude being least at the highest latitudes. It approaches 1.00 near the dip equator, remains at that value between approximately 0° dip - 45° dip N, then rises sharply to a peak value at 75^oN dip, before reaching normal value at the higher latitudes. The difference between the curves for the Quiet and Disturbed days lies in the magnitude of the ratios, the general shapes being the same. While the ratio value is 1.10 for the Q days at 75^oN dip, it is 1.25 for the D days at the same dip.

In sunspot minimum years, the ratio exceeds 1.00 between 90^oS dip and 45^oS dip though it is summer here; between 45^oS dip and 40^oN dip it is less than 1.00, then exceeds 1.00 between a short range of 40^oN dip - 70^oN dip, and at higher latitudes falls off below 1.00. The Q and D curves are not very different except at the southern high latitudes. Here the D(ratio) has a value of over 1.15 while

the Q (ratio) is slightly greater than 1.00. The peak value of the ratio at 55°N dip in the winter hemisphere is about 1.05.

June (f_oF_2)/ Equinox (f_oF_2).

In sunspot maximum years, in the southern (winter) hemisphere, the ratio is greater than 1.00 between 80°S dip and 60°S dip with a peak at 70°S. It becomes less than 1.00 between 60°S and 15°S and in the northern hemisphere (summer hemisphere) it continues to decrease, till the lowest values of 0.65 are reached at 70°N dip; at higher latitudes there is a short increase. The D and Q day variations follow much the same pattern, though the magnitudes differ notably at the higher latitudes. At 70°S, the D(ratio) is greater than 1.20 while the Q(ratio)is only 1.05. Above 70°N the D (ratio) is 0.85, while the Q (ratio) is 0.75.

In sunspot minimum years, the ratio is less than 1.00 at all latitudes. In the southern (winter) hemisphere, though there is a peak at 70°S dip, it still has a value less than 1.00. There is another peak at 20°S as in sunspot maximum; after this the ratio falls below 1.00 to reach a minimum at 60°N dip, then rises to 0.90 at the highest northern (summer) latitudes. The Q and D day values of ratios do not differ much.

(ii) Midnight hours

December (f_oF_2)/ Equinox (f_oF_2).

In sunspot maximum years, in the southern hemisphere (summer hemisphere) the night-time ratios between 80°S and 60°S dip are about 1.00, and the marked depression seen in the daytime is no longer there. From 55°S, the ratio gradually decreases below 1.00, to reach a minimum value at 70°N dip in the northern (winter) hemisphere; at higher latitudes it rises slightly. The night-time behaviour of the seasonal anomaly is just opposite to the daytime behaviour, the winter mid and high latitudes now experiencing decreased ratios in contrast to the daytime increase. D(ratios) are much larger than Q ratios in the whole northern (winter) hemisphere.

In sunspot minimum years in the southern (summer) hemisphere the ratio is about 1.30 between 90°S dip and 20°S dip, from where it drops sharply to reach 0.70 around the dip equator. It rises after 10°N dip with a peak value of 0.90 at 60°N dip, and drops at higher latitudes. The night-time behaviour here too differs from the daytime behaviour in that summer ratios are vastly enhanced, and winter ratios are decreased. The Q and D curves do not differ greatly even in magnitude.

151(a)

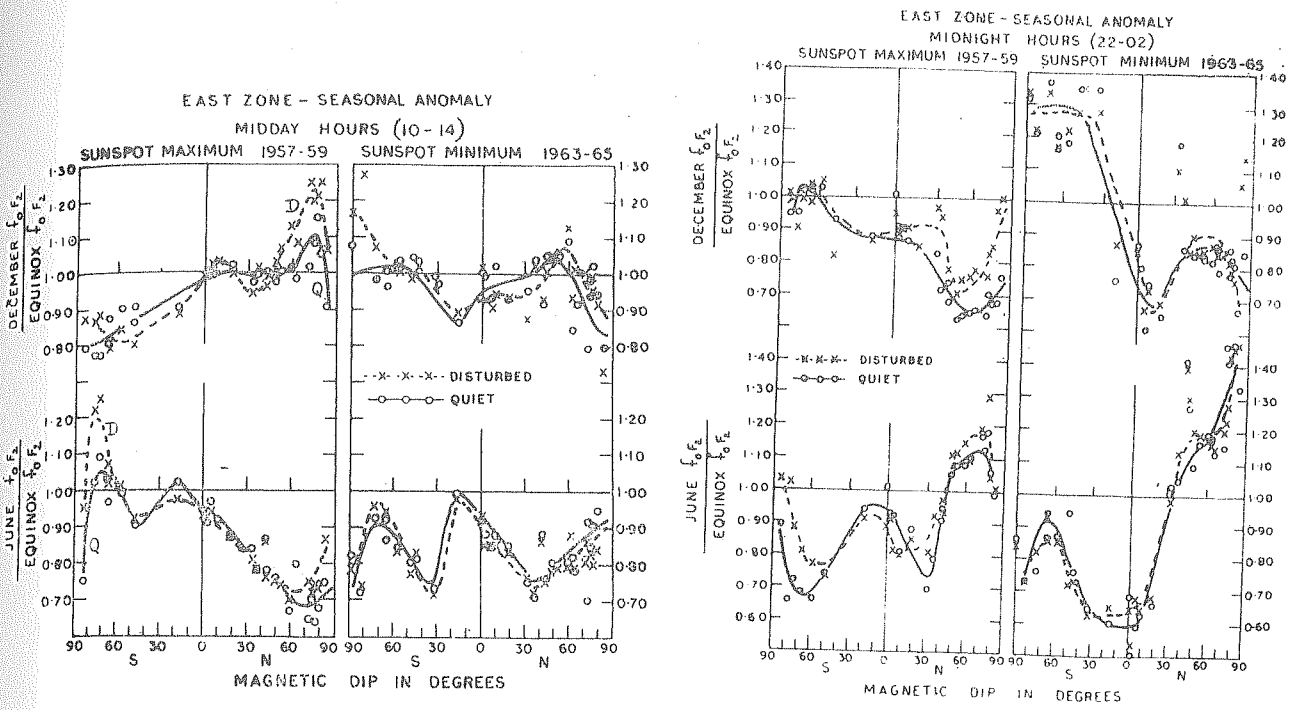


Fig. 5.6

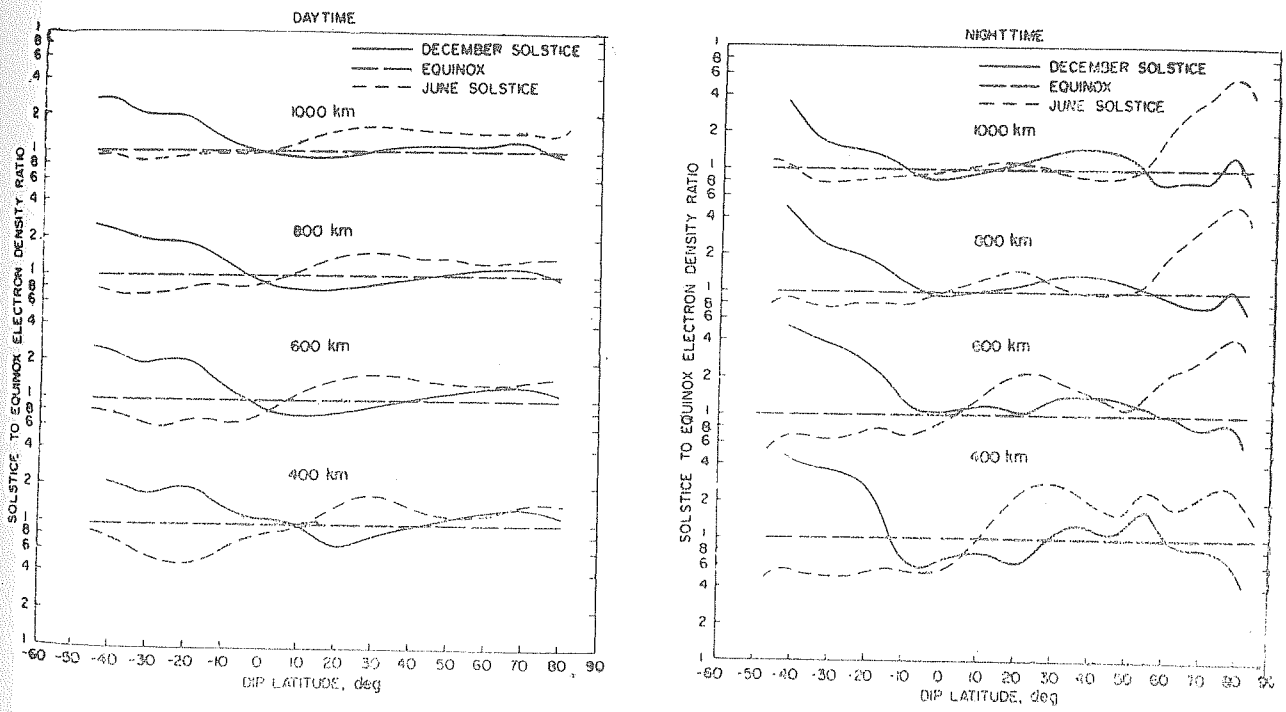


Fig. 5.7 Electron density ratios (Solstice/Equinox) at constant satellite altitudes versus dip latitude for (a) Day-time (b) Night-time (Chan and Colin 1969).

June (f_oF_2)/Equinox (f_oF_2)

In the high sunspot years, in the southern (winter) hemisphere, the ratio drops from about 1.00 at 90°S to 0.65 at 70°S dip, then rises to 0.95 at the dip equator. It falls to 0.75 at 30°N dip, increases to over 1.10 at 70°N dip, and drops at higher latitudes .. The daytime increase in winter ratios and decrease in summer ratios, are in the night-time replaced by a winter ratio-decrease, and summer ratio-increase. The D(ratios) are higher than the Q ratios notably at mid and high latitudes.

In sunspot minimum years, the ratio in the southern (winter) hemisphere reaches a peak value of 0.90 at 70°S dip, drops sharply to 0.60 at the dip equator, and steadily rises to a value of 1.40 in the northern(summer) hemisphere. No decrease is seen at higher latitudes. The night-time behaviour thus differs considerably from the day-time behaviour, notably in the summer hemisphere. The Q and D variations do not differ greatly.

(iii) Conclusions

(1) The seasonal anomaly is more marked in the daytime of the high sunspot years than in the low sunspot years. In the low sunspot years, clearly the southern hemisphere does not experience it. Any winter increase shown in the northern hemisphere is associated with the December anomaly (Rastogi 1960)

(2) Daytime and night-time seasonal behaviour in the high sunspot years are just reversed to each other in both solstices, the daytime winter peak being replaced by a night-time summer peak at high and mid-latitudes. This is not seen in low sunspot.

(3) The formation of a night-time summer peak at mid and high latitudes is particularly marked in the low sunspot years, as the Summer$\left(f_oF_2\right)$/ Equinox$\left(f_oF_2\right)$ratios increase by over 30%.

(4) The Solstice$\left(f_oF_2\right)$/ Equinox$\left(f_oF_2\right)$ ratio-variations for Q and D days do not differ greatly in pattern. Ratio values for D days are increased slightly as compared to Q days notably (1) at mid and high latitudes, and (2) in the high sunspot years. The change between D and Q ratios in the low sunspot years in comparatively less.

Chan and Colin (1969) have worked out the latitudinal variations of Solstice/Equinox Electron density ratios for a period 1962-63 (low sunspot) from Alouette I topside soundings. They have shown the variation for daytime hours (10.30-15.30 L.T.) and night-time hours (21.30 -03.30 L.T.) for heights of 400 km; 600 km, and 1000 km. Their curves are reproduced in Fig. 5.7 (Pg. 151(a)). The 400 km variations are the ones which come nearest to the variations at the h_{max} F_2 peak obtained in our study of f_oF_2.

When the daytime and night-time low sunspot variations of December (f_oF_2)/ Equinox (f_oF_2) ratios and June (f_oF_2)/ Equinox (f_oF_2) ratios in fig. 5.6 are compared with the corresponding 400 km ratios given in Fig. 5.7 the resemblance is striking. The night-time Summer/Equinox electron density increase is seen in both cases in both solstices. The daytime curves in Fig. 5.6 too resemble the corresponding curves in Fig. 5.7 in the general pattern of variation.

(b) Longitudinal variations in seasonal anomaly during IGY-IGC

The longitudinal differences are obtained by comparing the ratio variations with dip north and south for the West (American) zone, and the East (Australasian) zone . The period chosen is the high sunspot IGY-IGC (1957-1959), and the variations are shown separately for the midday hours (10-14) and midnight hours (22-02). The top curves represent the December (f_oF_2)/Equinox (f_oF_2) ratio variations while the lower curves represent those of the June (f_oF_2)/ Equinox (f_oF_2) ratio. Again these are shown for magnetically Quiet (Q) and Disturbed (D) conditions; the crosses with the dashed lines through them show the D(ratio) variations, and the circles with full lines through them show the Q (ratio) variations.

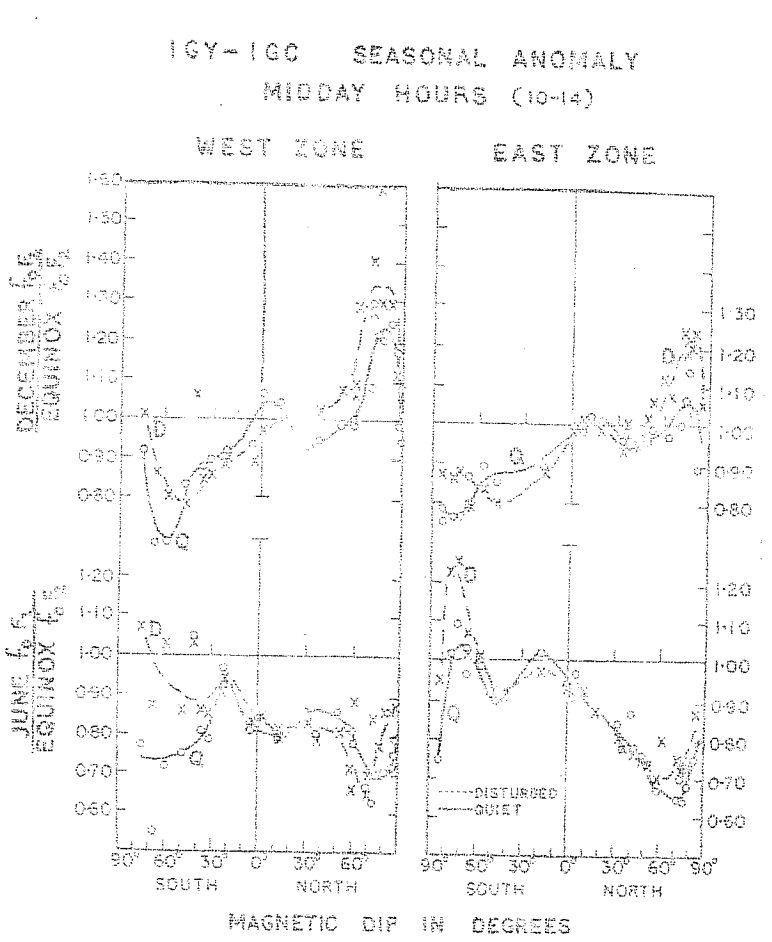
(i) Midday hours

December (f_oF_2)/ Equinox (f_oF_2)

The general pattern of variation is alike in the two zones except for small differences in the magnitude of the ratio as is shown in Fig. 5.8 (Pg. 155 (a)). In the southern (summer) hemisphere, the minimum values of the ratio occur at about 60°S dip, then the ratio rises to 1.00 at the dip equator. After a short drop till 40°N dip in the northern (winter) hemisphere, the ratio rises steeply to a peak at 75°N dip, and drops at higher latitudes. On D days, the ratios are higher than on Q days between 80°S dip and 45°S dip, lower between 45°S dip and 20°N dip, and higher at all latitudes beyond. All this is true for both zones. The decrease of ratio in the southern hemisphere, and the increase of ratio in the northern hemisphere are both of greater magnitude in the West zone than in the East zone.

June (f_oF_2) / Equinox (f_oF_2)

In the southern hemisphere, the ratio variations in the two zones are rather different. In the West zone, the ratio decreases below 1.00 from 80°S to 60°S dip, increases to 0.95 at 20°S dip. In the East zone, the ratio rises sharply from 80°S to a peak value of over 1.20 at 70°S dip, decreases to 0.90 at 40°S, then rises to 1.00 at 20°S dip. Beyond 20°S dip, the variation in both zones becomes similar.


IGY-IGC SEASONAL ANOMALY
MIDDAY HOURS (10-14)
WEST ZONE
EAST ZONE
DECEMBER f_0F_2 EQUINOX f_0F_2
JUNE f_0F_2 EQUINOX f_0F_2
DISTURBED
QUIET
SOUTH
NORTH
MAGNETIC DIP IN DEGREES

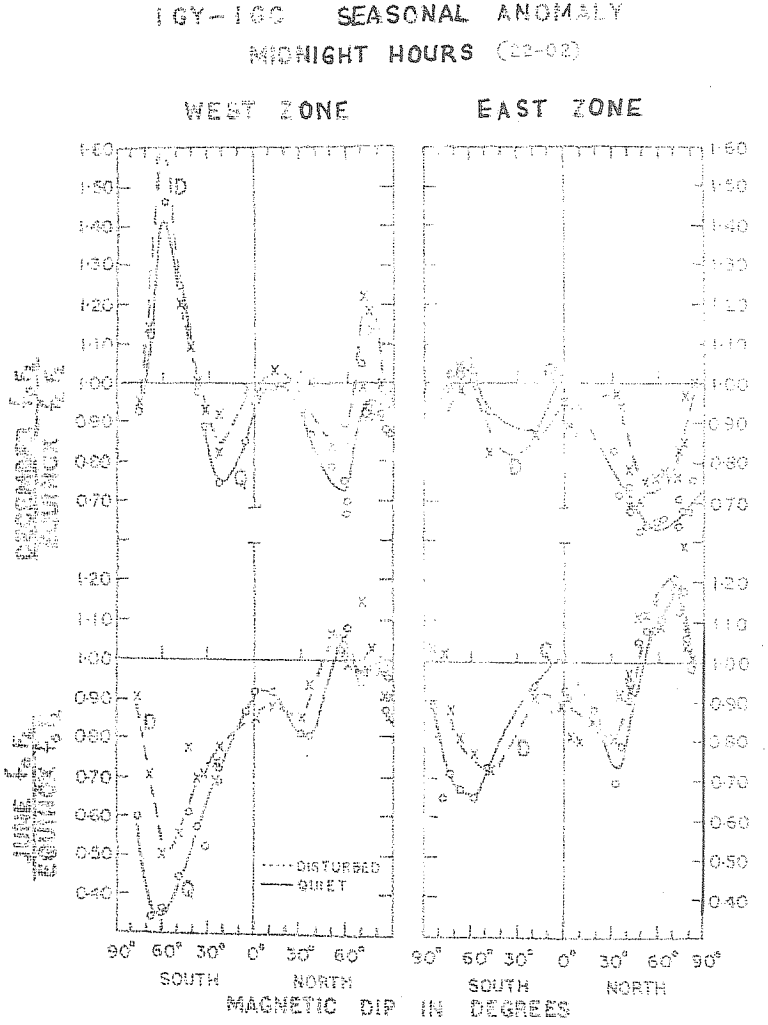

IGY-IGC SEASONAL ANOMALY
MIDNIGHT HOURS (22-02)
WEST ZONE
EAST ZONE
DECEMBER f_0F_2 EQUINOX f_0F_2
JUNE f_0F_2 EQUINOX f_0F_2
DISTURBED
QUIET
SOUTH
NORTH
MAGNETIC DIP IN DEGREES

Fig 5.8

155(a)

It decreases gradually to 0.65 at 70°N dip, then rises at higher latitudes. The D (ratios) are greater than Q(ratios) between 80°S to 45°S, and again from 70°N to 90°N dip in both zones.

(ii) Midnight hours

The night-time exhibits quite a complicated behaviour.

December (f_oF_2) / Equinox (f_oF_2) .

The night-time ratio variations differ for the two zones. In the West zone, there is a sharp rise of ratio from 75°S to 35°S dip with a peak value of over 1.40 at 60°S dip, decreases to 0.70 at 30°S dip, rises to 1.00 at the dip equator and drops to 0.70 at 60°N dip; it then rises to a peak at 70°N dip, and drops at higher latitudes.

In the East zone, the peak between 80°S and 50°S dip is very small with ratio around 1.00. Beyond 50°S dip, the ratio-variation is similar to that in the West zone, touching 1.00 at the dip equator; it drops to 0.65 at 60°N dip, then rises at higher latitudes. In both zones, D(ratios) are larger than Q(ratios) at all latitudes in the West zone, but only in the northern hemisphere in the East zone.

June (f_oF_2) / Equinox (f_oF_2)

The night-time ratio variations in the two zones are rather similar, except again for the magnitudes of the ratios.

The ratio drops from high latitudes in the southern (winter) hemisphere to low values at a dip of $60^{o}S$, then rises to around 1.00 at the dip equator. It then decreases till $30^{o}N$ dip, rises to a peak at $70^{o}N$ dip, and drops at higher latitudes. This is true for both zones. In the southern hemisphere the the ratio decreases to 0.35 in the West zone, and 0.65 in the East zone; the peak summer ratio value in the northern hemisphere is slightly greater than 1.00 in the West zone, and is 1.20 in the East zone. The D(ratios) are greater than Q (ratios) at all latitudes in the West zone, but only at the higher latitudes north and south in the East zone.

(iii) Conclusions

(1) The daytime seasonal variations in the two zones are very similar except for the ratio-magnitudes. At night too there is some resemblance.

(2) The night-time variations of the Solstice (f_oF_2)/ Equinox (f_oF_2) are reversed to those at day. The daytime winter increase of ratios is replaced by large night-time summer ratios in both zones, at mid and high latitudes.

(3) The D(ratio) values are greater than Q(ratio)values in both zones, markedly at mid and high latitudes.

(3) It is interesting to note that the general shape of the Solstice/Equinox (f_oF_2) ratio variations with dip remains the same on both Q and D days in all cases.

CHAPTER - VI

ELECTROJET EFFECTS ON THE EQUATORIAL AND LOW-LATITUDE F-REGION DURING MAGNETICALLY QUIET AND DISTURBED DAYS.

6.1 Introduction

The equatorial or geomagnetic anomaly of the F-region whose detailed behaviour during quiet conditions has been dealt with in Ch.2, and during Disturbed conditions in Ch. 5, is one of the most intriguing features of the ionosphere. The presence of a trough at the equator, and a crest at $\pm$ 30° dip in the latitudinal variation of f_oF_2 was first pointed out by Appleton (1946) and since then, a good amount of work has been done on it. Explanations of the feature have taken several forms. Mitra (1946) explained it as the gravitational diffusion to the two hemispheres of ionisation locally produced at great heights over the equator; Martyn (1949) invoked the, vertical $\vec{E} \times \vec{B}$ drift over the equator to be the factor which supplied ionisation at such great heights rather than solar U.V. radiation. Electron density distributions at different heights and latitudes were obtained by solving the continuity equation for the F-region (Moffett and Hanson (1965) Bramley and Peart(1965), Abur-Robb (1969). Baxter and Kendall (1968) included time-dependent electrodynamic terms, but Norton and Van Zandt(1964) were able to obtain electron density distributions similar to those over Huancayo without such a term, assuming only

temperature-dependent photoionisation and recombination rates. King and Kohl (1965) suggested that ion-drag by neutral winds contributes to the formation of the anomaly. Rastogi(1959) supported the idea of the $\vec{E} \times \vec{B}$ drift being responsible for the equatorial F_2 anomaly.

In this chapter, an attempt is made to examine the influence which equatorial electric fields have on the F_2 region ionisation observed at crest and trough stations. An index of these equatorial electric fields is

(1) $\triangle$ H the daily range in H at an equatorial station or

(2) the difference in $\triangle$ H between stations within and without the electrojet region (Nair et al., 1970)

Reasoning shows that this should be really valid for magnetically quiet conditions; during disturbed conditions, ring current effects are liable to be present, and the range in H would no longer be an index of ionospheric currents alone. It is however shown that during magnetically disturbed conditions and following geomagnetic storms, electron density distributions at the anomaly crest and trough are such as to suggest a weakening of equatorial electric fields. Rastogi et al., (1971) have shown that F-region meridional drifts at Thumba show a steady decrease with increasing K_p value. The study here is carried out for the Indian zone, the equatorial station being Kodaikanal (dip 3.6°N) and the crest station being Ahmedabad(dip 33°N).

The ionograms of the two stations were available and it was possible to work out the required electron density distributions.

Studies showing the relationship between electric fields and F-region electron densities have been made for the American zone by Dunford (1967, 1970), Duncan (1960) and McDouggall (1969). Bramley and Young (1968) showed that a very small downward drift of 5m/sec. is sufficient to destroy the equatorial anomaly in f_oF_2. Direct evidence of correlation between E-region horizontal drifts and F-region vertical drifts has been obtained from incoherent backscatter technique by Balsley and Woodman (1969). Kotadia and Patel (1970) showed that equatorial E_s generally decreases during magnetic disturbances.

6.2 Relationship between equatorial electrojet and low-latitude F_2-ionisation — high sunspot.

Some aspects of these features have been dealt with in the Paper which follows (Rastogi and Rajaram 1971). The relationship between the electrojet and the F-region electron densities at the crest (Ahmedabad) and trough (Kodaikanal) stations during both magnetically quiet and disturbed conditions has been shown for high sunspot conditions, the data being mainly that of IGY-IGC (though a few examples

of low sunspot are given).

(Paper 8 follows overleaf)

6.3 Quiet-day f_oF_2 variations at anomaly crest and trough for Strong and Weak electrojet

We now choose a low sunspot year, 1964, and show that it exhibits the same type of relationship between the electrojet and F-region ionisation at the anomaly trough and crest.

rnal of Pure & Applied Physics
gust 1971, pp. 531-536

Paper 8

lectrojet Effects on the Equatorial F-Region during Magnetically Quiet & Disturbed Days

R. G. RASTOGI & (Mrs) GIRIJA RAJARAM
Physical Research Laboratory, Ahmedabad 9

The critical frequency of the F_2-region at stations close to the crest and trough of the equatorial anomaly in the Asian zone have been studied in relation to the equatorial electrojet strength. It is shown that the midday bite-out in f_0F_2 at an equatorial station and the afternoon peak of f_0F_2 at a mid-latitude station are greatly enhanced on days of strong electrojet; on some weak electrojet days the noon bite-out of f_0F_2 at Kodaikanal is completely absent. Regarding the day-to-day variations, f_0F_2 at Kodaikanal is shown to decrease, and f_0F_2 at Ahmedabad to increase steadily with the increase of equatorial electrojet estimated by the difference in daily range of H between Trivandrum and Alibag. Electron density profiles computed for Kodaikanal indicate that the 'fountain' effect is operative normally at heights above 180 km and is greatly reduced or absent on a weak electrojet day or on magnetically disturbed days. The diffusion of electrons along the geomagnetic lines of force from the equatorial regions starts at higher altitudes in the morning, and gradually extends to the lower regions by midday; in the afternoon hours, the deficit of electrons during strong electrojet days or magnetically quiet days vanishes first at lower heights. It is concluded that the behaviour of the F_2-region at equatorial stations during magnetically disturbed days is equivalent to that on weak electrojet days. Thus, the equatorial electrojet current decreases in strength during magnetically disturbed days; it is suggested that this decrease is due to weakening of the equatorial east-west electrostatic field during magnetic disturbances.

equatorial anomaly in the F_2-region, which the latitudinal variation of daytime electron density shows maxima (crests) ns around 30° dip north and south with num (trough) directly over the magnetic has been one of the most speculated of the ionosphere since its discovery by [1]. The first explanation of this feature Mitra[2] who suggested that ionization locally l at great heights over the equator diffuses e effect of gravity to the two hemispheres e earth's magnetic field lines causing the ment of ionization in the vicinity of the crests. It was pointed out that the local et production of electrons at such great over the equator would be insufficient to the observed increase of electron density crests. Martyn[3] showed that the electron distribution with height at any station greatly affected by vertical transport of n. At equatorial regions, this vertical s suggested (Martyn[4]) as arising as a con- of eastward electric field E crossing the d magnetic field H. It was further sug- that the ionization so lifted upward near ator could diffuse horizontally towards d south along the magnetic lines of force sted by Mitra.

ng the diurnal development of the equa- nomaly as well as the daily variation of closely spaced equatorial stations, Rastogi[6] that the two anomalies of f_0F_2 at an equa- ation are due to the vertical drift of ioni- ver the magnetic equator after sunrise, followed by the pole-ward movement of ionization along the lines of force. Similar suggestions were advanced by Duncan[7], while comparing f_0F_2 at an equatorial station, Chimbote, with that of a tropical station, Panama.

Electron Density Calculations

On the basis of the above suggestion, quantitative calculations of electron density with height and latitude were made by Moffett and Hanson[8] and Bramley and Peart[9]. King and Kohl[10] invoke an additional effect of the ion drag by neutral winds to be a contributive factor in the formation of the anomaly. Detailed calculations using time-dependent electrodynamic terms have been computed by Baxter and Kendall[11]. Balsley and Woodman[12] have obtained a direct correlation between E-region horizontal drifts and F-region vertical drifts using incoherent backscatter technique at Jicamarca. Rastogi[13,14] has shown evidence of such vertical movement in the equatorial ionosphere in the vertical upward moving 'kinks' observed in ionograms obtained at Thumba and Kodaikanal. It is thus evident that the equatorial F_2-region is closely associated with the equatorial electrojet current. The relationship between the equatorial anomaly and the equatorial electrojet has been studied by Dunford[15,16] and McDougall[17].

In this paper, we have studied electron density distribution in the equatorial anomaly during magnetically calm days with strong and weak electrojet intensities, as well as during magnetically quiet (Q) and disturbed (D) days. The daily range of the horizontal component H

at Kodaikanal has been taken to represent the strength of the equatorial electrojet current. Also studied is the effect of the equatorial electrojet current intensities on the daily variation of f_0F_2 at stations situated on the crest and trough of the anomaly in the Indian zone. Rastogi[18] has shown that the crest of the equatorial anomaly in the Asian zone occurs very close to the latitude of Ahmedabad or Okinawa, while Kodaikanal is situated close to the trough. It has been shown that f_0F_2 at Kodaikanal has two maxima occurring around 08 and 16 hrs, irrespective of the epoch of solar activity (Rastogi and Sanatani[19]). At stations near the crest, one observes a single maximum of f_0F_2 around 15 hrs in the low sunspot years, but the high values of f_0F_2 continue even after sunset during years of high solar activity.

The daily variations of f_0F_2 at the trough and crest were compared on three days in the same month when H varied appreciably but the magnetic character figures did not indicate any disturbance. Under such conditions the diurnal range of H may be taken as an index of the electrojet current strength. A day of large H range is a day of strong electrojet current, while one of small H range is a day of weak electrojet. An example of such a set showing daily variation of H at Kodaikanal, and f_0F_2 variations at Kodaikanal and Okinawa for the month of January 1958 is depicted in Fig. 1. On the day of strong electrojet, the daily variation of f_0F_2 at Kodaikanal shows the lowest midday value of f_0F_2 with the greatest amount of noon bite-out. On the weak electrojet day, the daily variation of f_0F_2 does not show any bite-out and is maximum around noon with very high values, which seems unusual for an equatorial station. On a medium electrojet day, the value of midday f_0F_2 lies in between, and a weak bite-out is evident. Comparing the variations of f_0F_2 at Okinawa (crest) for the same days, it is seen that the highest noon values of f_0F_2 occur on the strong electrojet day while the lowest occur on the weak electrojet day which is opposite to what happens for midday f_0F_2 at Kodaikanal. This clearly shows that the strength of the equatorial electrojet contributes significantly to the equatorial f_0F_2 bite-out, and the tropical enhancement of f_0F_2 in the afternoon hours.

The effect of the equatorial electrojet on f_0F_2 at crest and trough stations was further studied by comparing the daily variation of f_0F_2 at Kodaikanal and Ahmedabad during a weak and strong electrojet day for each month of the year 1965, as shown in Fig. 2. In each block, the lower curves refer to Kodaikanal, while the upper ones are for Ahmedabad. The variations on strong electrojet days are shown by full lines while those on weak electrojet are shown by dashed lines. The dates as well as the diurnal range of the horizontal field component H are indicated close to the curves for Ahmedabad. Referring to the curves for Kodaikanal it is clearly seen that in each of the months the midday f_0F_2 is more on a weak electrojet day than on the strong electrojet day. Further, the midday bite-out is generally deeper on strong electrojet days, and is less or even absent on weak

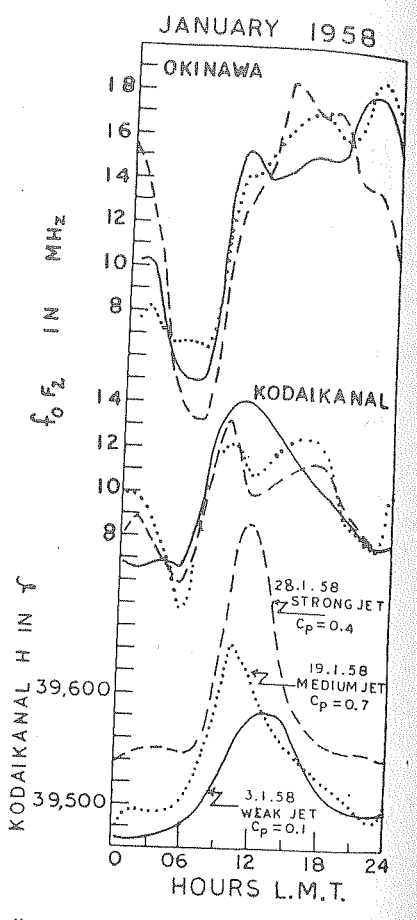
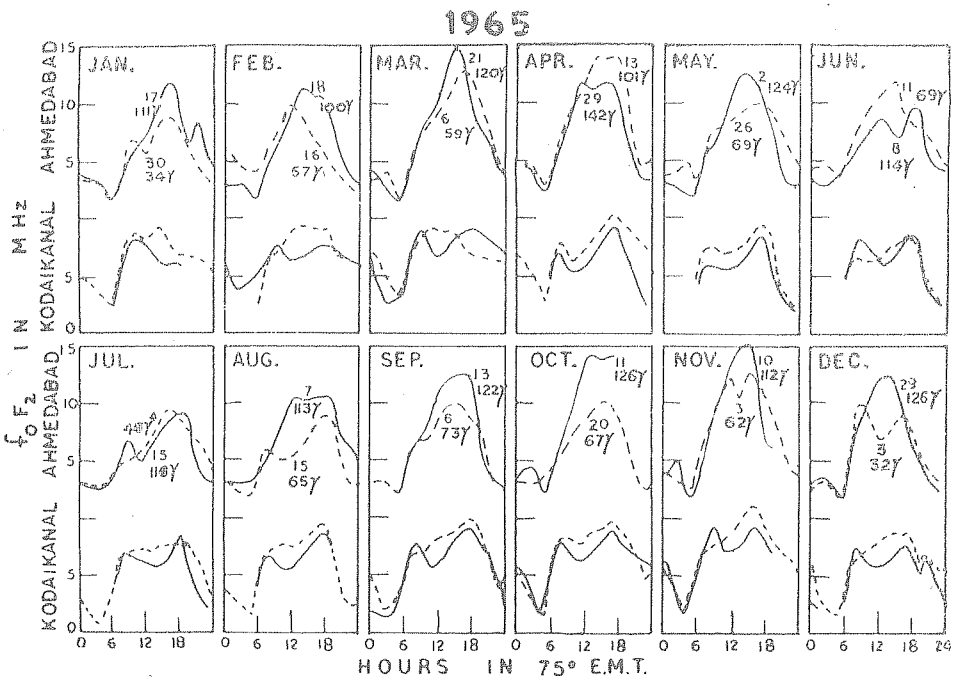
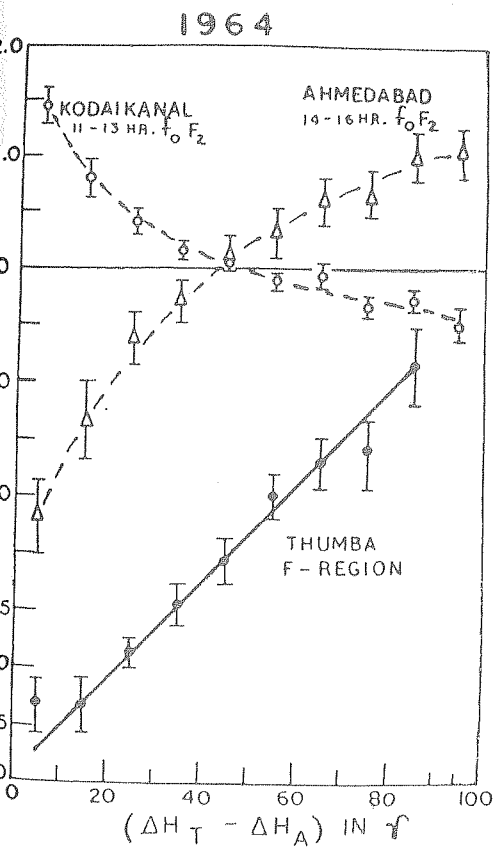


Fig. 1 — Daily variation of H at Kodaikanal and f_0F_2 at Kodaikanal and Okinawa observed in Jan. 1958

electrojet days. An exception to this is noticed for the equinoctial month of April when the average electrojet is stronger than in other months. Thus, the electrojet strength on any of the days in April 1965 was above the minimum threshold value required to produce the bite-out of f_0F_2. Referring to the f_0F_2 variations at Ahmedabad, it is seen that in most of the months, the afternoon value of f_0F_2 is larger on the strong than on the weak electrojet days. The month of April was exceptional as the equatorial bite-out was present on almost all days; in the local summer months of June and July, a noon bite-out is observed at tropical latitudes (Rastogi and Sanatani[20]). Nair *et al.*[21] have suggested that the diurnal variation of H at a ground station could be contributed by electrojet current which would be present only at euqatorial stations — say Trivandrum in our longitude — as well as due to magnetospheric currents, the effect of which would be of the same order at both equatorial and mid-latitude stations, namely Trivandrum as well as Alibag. The difference of the daily ranges at the two stations, i.e. $(\Delta H_T - \Delta H_A)$ would represent more precisely the contribution due to ionospheric currents flowing over the magnetic equator at the E-region heights. Fig. 3 shows the correlation of F-region horizontal drifts at the equatorial station Thumba, as well as for the f_0F_2 c



Comparison of daily variation of f_0F_2 at Kodaikanal and Ahmedabad during weak (- - - -) and strong (——) electrojet days for each month of the year 1965



Correlation of F-region horizontal drifts at the equatorial station as well as of the f_0F_2 deviations at an equatorial and crest stations with $\Delta H_T - \Delta H_A$

deviations obtained at an equatorial and crest stations with $(\Delta H_T - \Delta H_A)$. It is seen that the horizontal F-region drift increases linearly with electrojet range $(\Delta H_T - \Delta H_A)$— obviously the vertical drifts in the F-region would also increase with increase in horizontal drift velocity. The values of f_0F_2 at Kodaikanal during the midday hours (11-13 hrs) is seen to decrease with increase of electrojet while the f_0F_2 values at Ahmedabad for the noon hours (14-16 hrs) show a steady increase with electrojet. It may be noticed that for the same change in $(\Delta H_T - \Delta H_A)$, the change in f_0F_2 is larger for Ahmedabad than for Kodaikanal. This could be due to the F_2 ionization being spread over a greater vertical height at the equator than at tropical latitudes. The ionization transported away from the equator would be distributed over a comparatively smaller vertical column at the crest regions, giving rise to slightly greater change in f_0F_2.

Daily Variations of f_0F_2 on Magnetically Quiet and Disturbed Days

To study the effect of magnetic activity on f_0F_2 at the equator, daily variations of f_0F_2 and H at Kodaikanal were compared on a quiet day (C_p low) and a disturbed day (C_p high) both of the same month. An example of these variations for 3 different months are shown in Fig. 4. As is well known, during a quiet day, the daily variation of H is smooth with a maximum shortly before midday, while on a disturbed day, the mean variation of H is greatly decreased, the variations are irregular, and the daily pattern of midday maximum is also

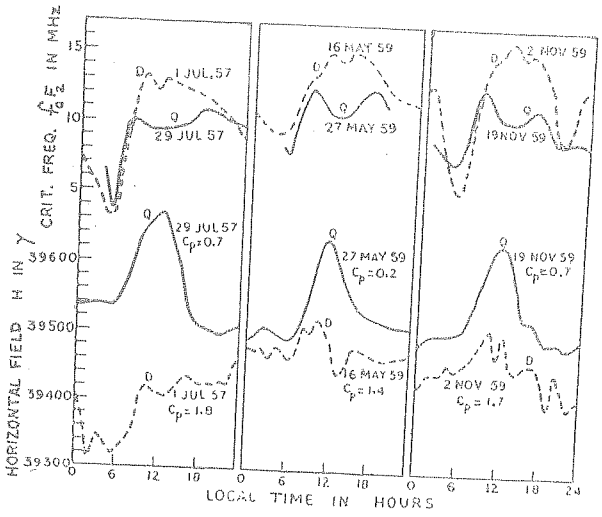


Fig. 4 — Daily variations of f_0F_2 and H on quiet (——) and disturbed (- - - -) days

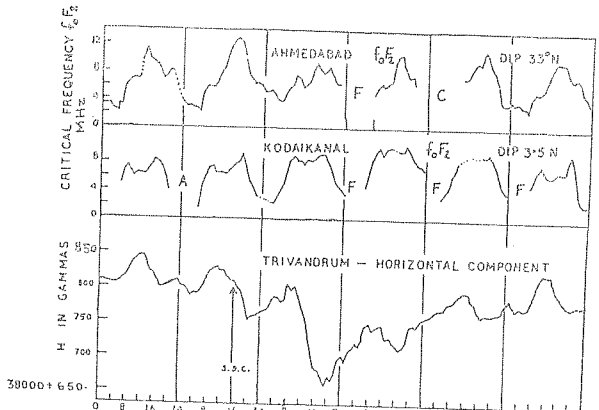


Fig. 5 — Effect of magnetic storm on f_0F_2 and H at equatorial station, Kodaikanal, and crest station, Ahmedabad

obliterated. These features are clearly seen from the diagram. The variation of f_0F_2 on quiet days of these months show significant bite-out while the curve corresponding to disturbed days do not show any decrease around midday; rather a maximum is evident around or even before noon. This suggests that the daily variation of f_0F_2 at Kodaikanal on magnetically disturbed days is analogous to that on a weak electrojet day.

The effect of a particular magnetic storm on the f_0F_2 variations at equatorial station, Kodaikanal, and crest station, Ahmedabad, is shown in Fig. 5. The lowest curve shows the H variations of the storm at an equatorial station, Trivandrum, commencing from over 24 hr before s.s.c., marked by an arrow — to over 72 hr after the storm. The f_0F_2 variations are shown for the same period. During the days when the storm is in progress — indicated by the depression of the magnetic field H — the f_0F_2 values at Kodaikanal have increased while those at Ahmedabad have decreased as compared to the corresponding values on an undisturbed day. Further the noon bite-out in f_0F_2 at Kodaikanal is absent on the storm days, probably indicating weakening of transport of electrons away from the equator during disturbed conditions.

Electron Density Distributions

In order to determine the effect of the equatorial electrojet and magnetic activity on the electron density at different heights of the ionosphere rather than at the F_2 peak, N-h profiles were calculated from the ionograms for Kodaikanal. This was done for selected weak and strong electrojet days, as well as for averaged 5 international quiet and 5 international disturbed days of a particular month. The topside profile was calculated by fitting a Chapman distribution at the F_2 peak. These sets of profiles are shown in Fig. 6. To the left are the N-h profiles for two strong and weak electrojet days of January 1958 for the different hours, commencing from 07 to 19 hrs — the lines correspond to the profile for the strong electrojet (S) day and the dashed ones to the weak electrojet (W) day. To the right are the averaged profiles for the 5 quiet (Q) and 5 disturbed (D) days of July 1957 — the full lines represent the quiet days and the dashed lines represent the disturbed days. In both cases, the dotted area represents the deficit of electrons on the full line day (S or Q) as compared to the dashed line day (W or D).

It is noted that even to start with, the electron density was more on a weak than a strong electrojet day, the difference being mainly in the top part

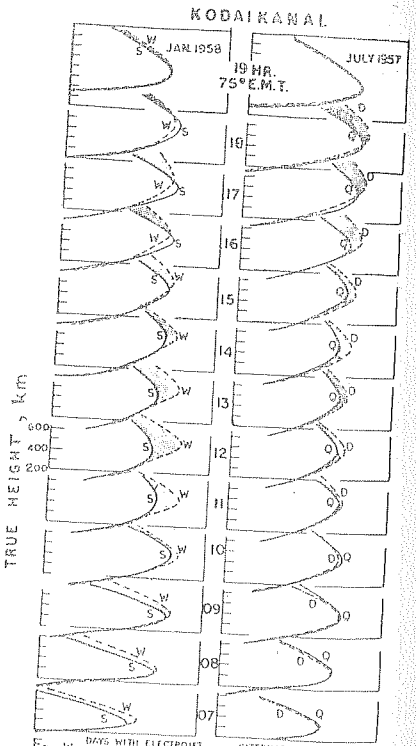
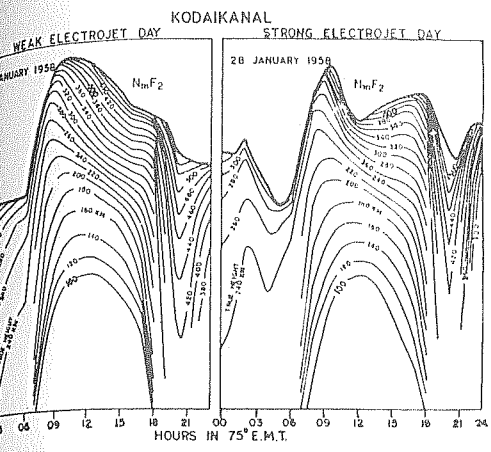


Fig. 6 — Profiles of electron distribution calculated by fitting Chapman distribution at the F_2 peak at Kodaikanal



Diurnal variation of electron density at fixed of ionosphere on days of strong and weak electrojet

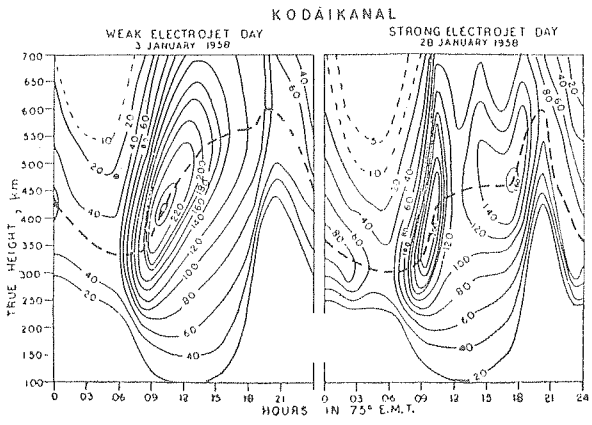


Fig. 8 — Diurnal variation of height contours of constant electron density (in units of 10^4 electrons/cm^3) at Kodaikanal on weak and strong electrojet days

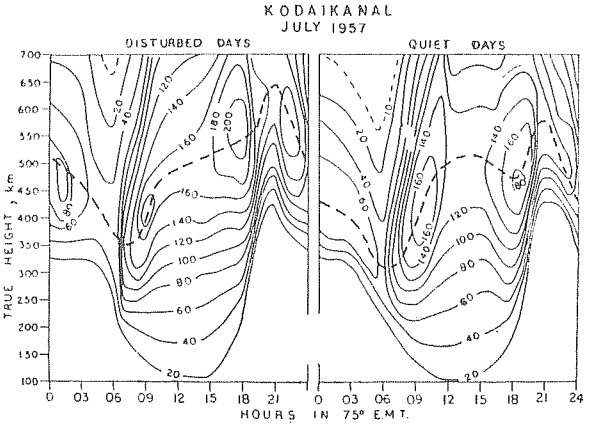


Fig. 9 — Comparison of constant electron density (in units of 10^4 electrons/cm^3) contours for quiet and disturbed days at Kodaikanal

profile. At 09 hrs and more so at 10 hrs erence in electron density between the two xtends to heights lower than the F_2 peak. day — 11 and 12 hrs — the electron density on S than on W days from heights starting as 200 km. With further progress of the his difference starts vanishing from low till about 15 hrs when the difference only above the F_2-layer. This suggests e daily cycle of removal of the electrons from atorial F_2 to higher latitudes as a consequence fountain effect created by the $E \times B$ force. irst at higher heights, and remains longer igher height. A more or less similar pattern due to the magnetic activity such that a lectrojet day corresponds to a magnetically ed day, and a strong electrojet day corres- o a magnetically quiet day.

daily variation of electron density for fixed of the ionosphere at intervals of 20 km 0 km to the F_2-layer peak for the days of and weak electrojet are shown in Fig. 7. en that daily variation of electron density y symmetrical at lower heights of the n — but as the height increases, the electron seems to become higher in the morning the evening hours. This departure seems mence from 160 km which is roughly the of the F_1 peak. During the weak electrojet electron density at any height above 200 km maximum in the forenoon hours and ally decreases during the latter part of y. The maximum electron density N_mF_2 clear maximum close to noon without any on of bite-out. On a strong electrojet day, a rapid decrease of electron density after rning peak, and it increases after midday hts above 340 km. There is a significant of N_mF_2 around midday.

ron density profiles can also be shown as iation of height contours for constant elec- nsity values. Such contours for the strong ak electrojet days are shown in Fig. 8. It that on a weak electrojet day, the contours maximum at about 10 hrs and the height of the F_2 peak continually increases from 09 to about 19 hrs as shown by the thick dashed line. Similar profiles of electron density obtained at Huancayo have been explained by Norton and Van Zandt[22] in terms of rapid photo-ionization and recombination with a temperature rapidly increasing in the morning, and constant in the afternoon, without any necessity for the $E \times B$ drift. The contours for the strong electrojet day show two maxima, and a very strong peak of h_mF_2 is seen at 19 hrs. It is interesting to note that the height of the F_2 peak remains almost constant during 10-16 hrs when the main bite-out of electron density occurs. This suggests that the electrons are removed from the F_2 peak as fast as they are produced or lifted from the lower regions.

Comparing similar contours for quiet and disturbed days shown in Fig. 9, we find disturbed days contours are similar to that of a weak electrojet day. The height of the F_2 peak increases steadily from 09 to 19 hrs and there is a major peak of electron density in the evening hours. The contours on a quiet day compare well with those of a strong electrojet day, namely the two loops of maxima in the morning and evening hours, and

the height of the F_2 peak does not increase steadily with time after the start of the bite-out effect.

Conclusion

1. The amount of noon f_0F_2 bite-out at an equatorial station is proportional to the strength of the equatorial electrojet.

2. The afternoon increase of f_0F_2 at a crest region and the noon increase in bite-out at an equatorial station are complementary to one another.

3. The daily variation of f_0F_2 and the electron density profiles on a disturbed day are analogous to that on a weak electrojet day; the daily variation on a quiet day is analogous to that on a strong electrojet day.

It is suggested that the magnetic disturbance effect at the region in the equatorial anomaly trough is a consequence of the decreased 'fountain' effect. This could arise because of decrease of the east-west electrostatic field, and thereby the decrease of the equatorial electrojet during magnetically disturbed conditions.

Acknowledgement

The authors are grateful to Dr M. K. V. Bappu, Dr J. C. Bhattacharya and the staff of the Astrophysical Observatory, Kodaikanal, for their extended cooperation in making this study possible. Thanks are due to Prof. K. R. Ramanathan for helpful discussions throughout the course of the work.

References

1. Appleton, E. V., *Nature, Lond.*, **157** (1946), 191.
2. Mitra, S. K., *Nature, Lond.*, **158** (1946), 668.
3. Martyn, D. F., *Proc. R. Soc.*, **189A** (1947), 241.
4. Martyn, D. F., *Proc. R. Soc.*, **194A** (1949), 429.
5. Martyn, D. F., *Physics of the ionosphere* (The Physical Society, London), 1955, 254.
6. Rastogi, R. G., *J. geophys. Res.*, **64** (1959), 727.
7. Duncan, R. A., *J. atmos. terr. Phys.*, **18** (1960), 89.
8. Moffett, R. J. & Hanson, W. B., *Nature, Lond.*, **206** (1965), 705.
9. Bramley, E. N. & Peart, M., *J. atmos. terr. Phys.*, **27** (1965), 1201.
10. King, J. W. & Kohl, H., *Nature, Lond.*, **206** (1965), 699.
11. Baxter, R. G. & Kendall, P. C., *Proc. R. Soc.*, **A304** (1968), 171.
12. Balsley, B. B. & Woodman, R. F., *J. atmos. terr. Phys.*, **31** (1969), 865.
13. Rastogi, R. G., *Nature, Lond.*, **225** (1970), 258.
14. Rastogi, R. G., *Proc. Indian Acad. Sci.*, (1970), (in press).
15. Dunford, E., *J. atmos. terr. Phys.*, **29** (1967), 1489.
16. Dunford, E., *J. atmos. terr. Phys.*, **32** (1970), 421.
17. McDougall, J., *Proceedings of the third international symposium on equatorial aeronomy* (Physical Research Laboratory, Ahmedabad), 1969, Vol. 2, 269.
18. Rastogi, R. G., *J. atmos. terr. Phys.*, **18** (1960), 331.
19. Rastogi, R. G. & Sanatani, S., *J. atmos. terr. Phys.*, **25** (1963), 739.
20. Rastogi, R. G. & Sanatani, S., *Annls Géophys.*, **28** (1968), 75.
21. Nair, K. N., Rastogi, R. G. & Sarabhai, V., *Nature, Lond.*, **226** (1970), 740.
22. Norton, R. B. & Van Zandt, T. E., *J. atmos. terr. Phys.*, **26** (1964), 1047.

Fig. 6 (a) (Pg. 162(a)) shows the f_oF_2 variations at Ahmedabad and Kodaikanal on identical days, one being a day of strong electrojet, and one a day of weak electrojet. Such pairs of days have been chosen for each month of 1964, care being taken to see that only magnetically calm days are considered; the intensity of the electrojet is determined from the range of the H variation at the equator on these days . The range is H is defined as

[Mean H (11,12,13) hr –Mean H (00, 01, 02,03, 04) hr.] the hours being taken in 75° E.M.T. A day with large range in H is considered as a day with large electrojet current intensity, and a day with small range in H as a day with small electrojet current intensity. The strong electrojet days (S) are shown by full lines, the weak electrojet days (W) by dashed lines, and the dates and the corresponding equatorial range of H in gammas are indicated against each.

It is seen without exception that it is on the strong jet days that Kodaikanal the equatorial station shows the greatest midday bite-out in f_oF_2 , and on the same days the crest station Ahmedabad exhibits the

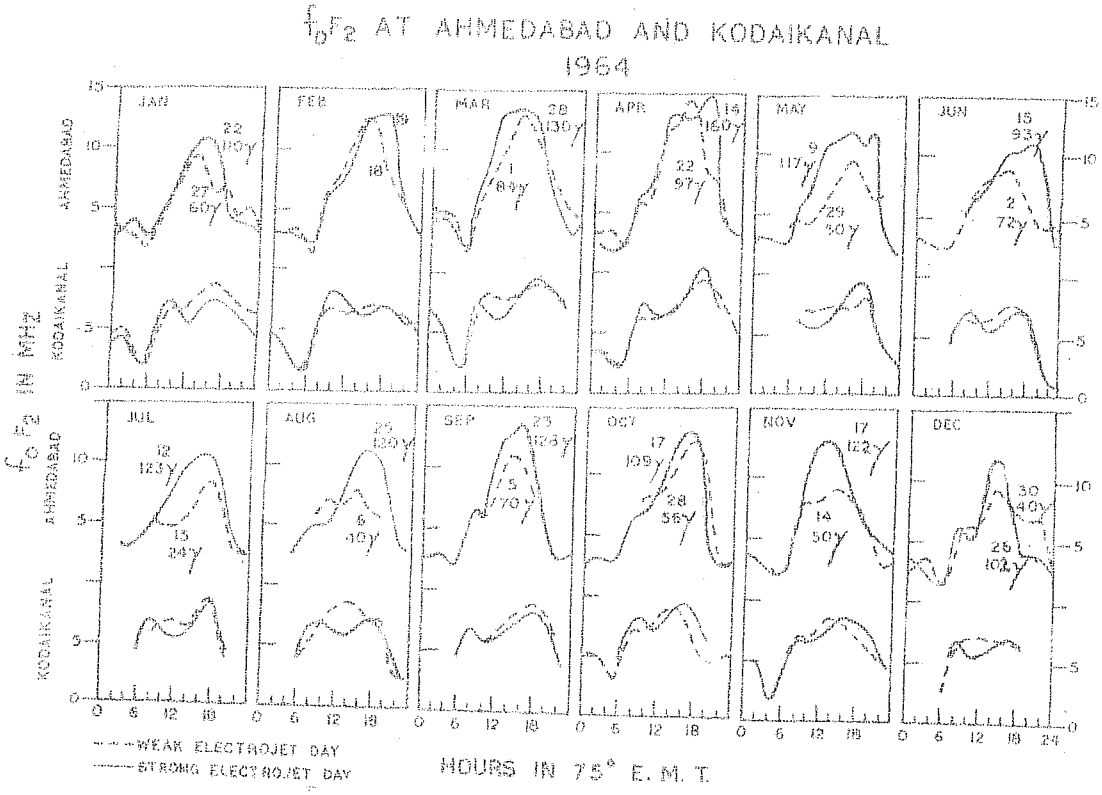

f_0F_2 AT AHMEDABAD AND KODAIKANAL
1964
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
f_0F_2 IN MHz
AHMEDABAD
KODAIKANAL
WEAK ELECTROJET DAY
STRONG ELECTROJET DAY
HOURS IN 75° E. M. T.

FIG 6.a

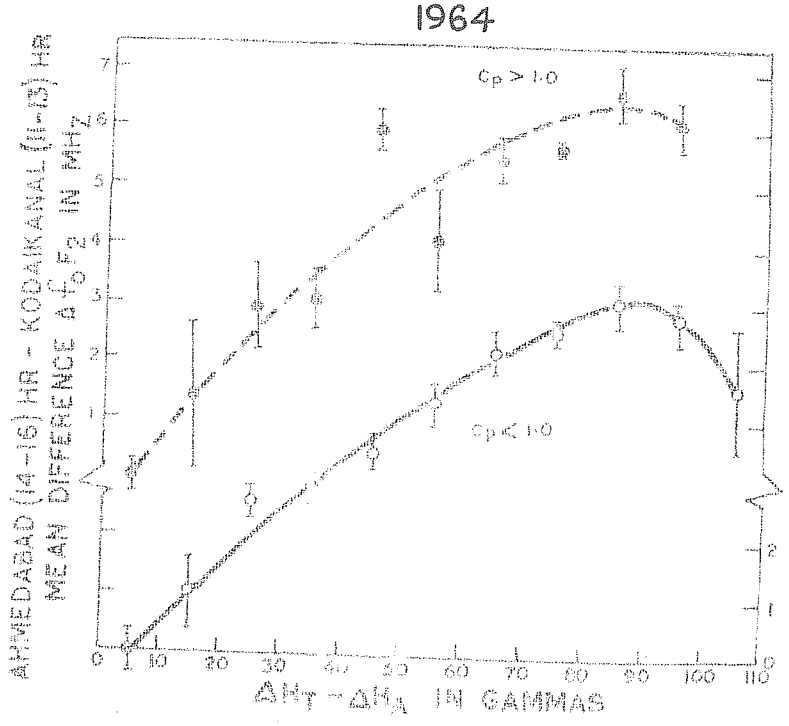

1964
AHMEDABAD (14-16) HR - KODAIKANAL (11-13) HR
MEAN DIFFERENCE AT f_0F_2 IN MHz
$C_p > 1.0$
$C_p < 1.0$
$\Delta H_T - \Delta H_A$ IN GAMMAS

FIG 6.b

largest frequencies, with a peak around 15 hr. In contrast, on the weak jet days Kodaikanal shows less midday bite-out with overall higher values of f_oF_2 ; correspondingly on the same days, Ahmedabad experiences decreased frequencies. This is seen in each month of 1964, and suggests that on a strong jet day, there is more vertical uplift of ionisation from the equator, and transport (associated with higher heights) to the crest, while on a weak jet day, there is less uplift, and less transport. The same feature was shown for the different months of 1965 in Fig. 2 of the Paper . The only exception here was the month of April which showed uniformly high values of jet strength throughout, and no reduction of midday f_oF_2 bite-out at the equator on any day of that month. The decrease in daytime bite-out with increase in magnetic disturbance was noticed by Bhargava and Subrahmanyan (1962) at Kodaikanal.

6.4 Relationship of $\triangle H_T - \triangle H_A$ with f_oF_2 at anomaly crest and trough.

In Fig. 6 (b) (Pg. 162 (a)) we show the difference between peak f_oF_2 at Ahmedabad (14-16 hr.) and the trough f_oF_2 at Kodaikanal (11-13 hr.) plotted as a function of $\triangle H_T - \triangle H_A$ (which represents the difference in range of H between Trivandrum within the electrojet region and Alibag outside the electrojet region). This difference in $\triangle H$ is taken as an index of the electrojet current.

The difference $\triangle f_o F_2$ is shown separately for quiet days ($C_p < 1.0$) and disturbed Days ($C_p > 1.0$) of 1964.

Both curves show that the difference steadily increases with $\triangle H_T - \triangle H_A$, till at a certain value of $\triangle H_T - \triangle H_A$ (85 γ) in both cases, the difference starts decreasing. Error bars are shown on both curves; it is seen that the trend is better for $C_p < 1.0$, and that there is some scatter for $C_p > 1.0$. The curves again suggest that large electrojet intensities cause the removal of F_2 ionisation from equatorial regions, and it is transported to the crest regions. The decrease in $\triangle f_o F_2$ beyond 85 γ is interesting. It could be caused by several factors, two of these being:

(1) beyond this value, probably $\triangle H_T - \triangle H_A$ ceases to be an index of electrojet current. $\triangle H_T$ may be caused by polar currents closing through low-latitudes, and ring currents, apart from purely ionospheric currents.

(2) For very large values of $\triangle H_T - \triangle H_A$ the equatorial F_2 peak may be raised to heights where electron loss rates are considerably reduced, and the reduced loss compensates for the drop in $f_o F_2$ caused by the transport of ionisation to the crest region.

In any case, this feature is an important one, and requires more investigation. The variations for 1964

of the $\triangle f_o F_2$ at Ahmedabad (14-16 hr. minus daily mean) and at Kodaikanal (11-13 hr. minus daily mean) with the parameter $\triangle H_T - \triangle H_A$ is shown in Fig. 3 of the Paper ; also shown is the variation of Thumba F-region horizontal drifts as a function of the same parameter.

6.5 Quiet-day equatorial electron density distributions for Strong and Weak electrojet.

Of the pairs of days in 1964 with strong and weak electrojets, shown in Fig. 6 (a) (Pg. 162 (a)) those for the months of August and December have been chosen, and their electron density distributions at Kodaikanal worked out from the ionograms.

(i) The electron densities at constant heights for these pairs of days are depicted in Fig. 6(c)(Pg.166(a)) The weak electrojet days are shown to the left and the strong electrojet days to the right. The $N_{max}\ F_2$ variations are shown by thick lines, and exhibit the largest bite-out on strong jet days. The bite-out effect is seen at lower region heights, and here it starts earlier and ends later; the morning and evening peaks approach closer with increasing height. On weak jet days, the bite-out in $N_{max}\ F_2$ is not seen at all; some bite-out is seen at the lower heights on such days. The profiles are mostly for the daytime hours. In the pre-down hours, no reflection traces are seen in the ionograms as the electron density

is too small to be recorded by the equipment; spread F conditions set in after sunset. The electron density variations at the various heights are clearly seen. Such profiles for a pair of strong and weak jet days for high sunspot years are plotted with a logarithmic scale for electron density in Fig. 7 of the Paper. It shows similar characteristics, except that the forenoon peak in N_{max} F_2 is larger as is typical of high sunspot years.

(ii) The N-h profiles for these two sets of strong and weak jet days are shown in Fig. 6 (d) (Pg. 166 (a)). The first two blocks show the two sets of days from 07 to 12 hr. while the second two blocks show the same sets from 13 to 18 hr. The full lines show the strong electrojet days while the dashed lines are the weak electrojet days. The profiles are shown from a height of 100 km to 550 km with the electron density in electrons/cm^3 as the abscissa.

The August set shows an excess of electron density in the topside on weak electrojet days, but a deficit in the lower side, till 09 hr. At 10 hr the excess during weak electrojet extends to the lower side too, but from 11 hr. onwards, there is considerable excess in the lower side, with a deficit in the topside. The greatest excess is at 14 hr. and 15 hr., after which it gradually decreases and at 18 hr. there is a deficit in both bottonside and topside on weak electrojet days. It is

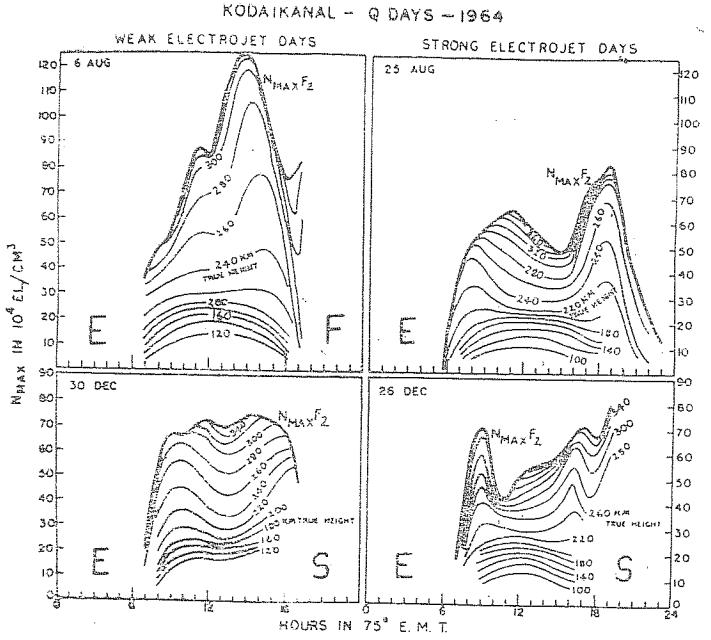


Fig. 6.c

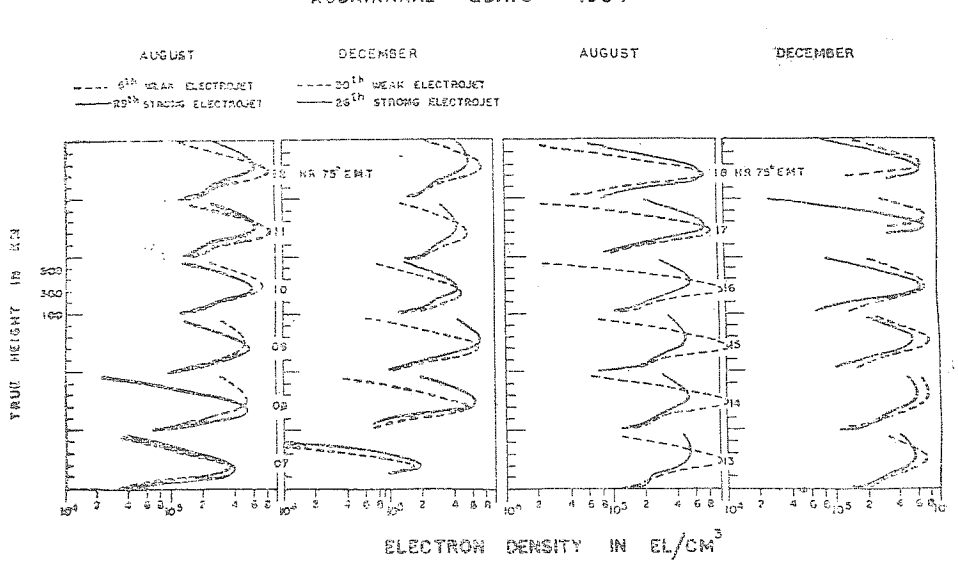


Fig. 6.d

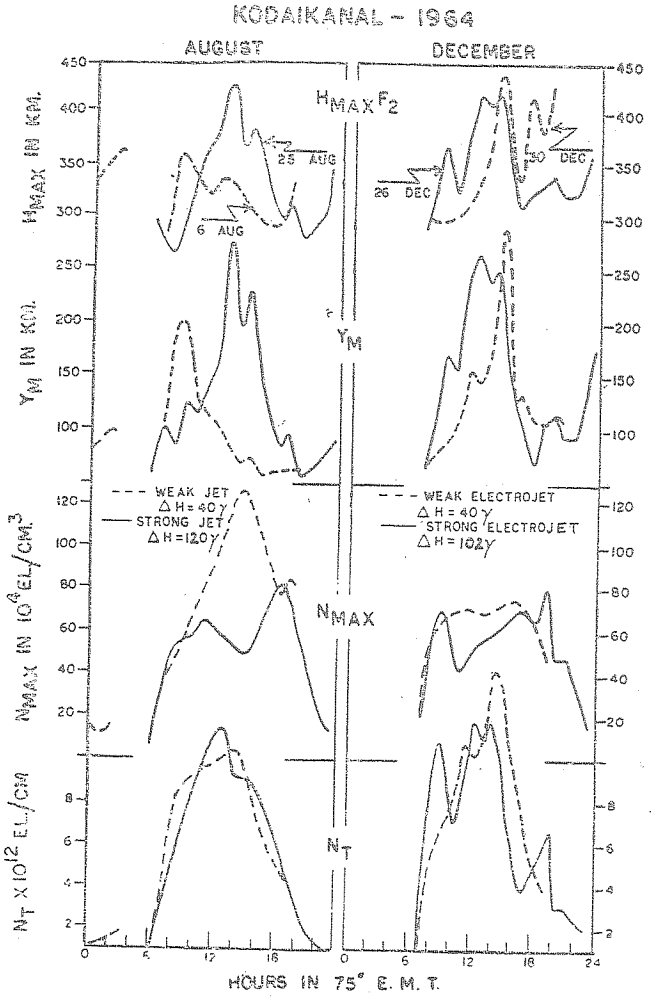


Fig. 6.e

worth noting that the weak electrojet day profiles are remarkably different from the profiles of the strong electrojet day.

The December set shows a different trend. The ionisation on the weak jet day shows an excess in the bottomside from as early as 08 hr. though there is a large deficit in the topside. With progress of time the bottomside excess increases while the topside deficit decreases till 13 hr. Later on, a gradual increase on weak jet days starts at the topside too, and at 17 hr. and 18 hr. the ionisation in the bottomside decreases. Once again the profile shapes on the strong and weak jet days are quite different.

The pattern of variation on the strong and weak jet days in August and December is different, but the main point to be noted is that in both months, between 10 hr. and 16 hr. when daytime f_0F_2 bite-out on the strong jet days is seen, the ionisation in the bottomside is notably larger on the weak jet day than on the strong jet day - that means there is a deficit of ionisation on the strong jet day. The deficit of ionisation could have been caused by the transportation of electrons upward and partly away to the anomaly crest. The dissimilarities in the topside are likely to arise from the different heights

associated with the different seasons of the August and December months. Such a set of curves comparing electron density profiles on strong and weak electrojet days of January 1958 (a high sunspot year) is shown on the left-hand side of Fig. 6 of the Paper. It is also characterised by an excess of ionisation on the bottomside on a weak electrojet day, though here the ionisation excess extends to the topside too. The cross-over of weak electrojet ionisation and strong electrojet seems to occur at the larger heights, associated with high sunspot. On the right-hand side of the same figure are shown the corresponding profiles of a magnetically Quiet and Disturbed day of a high sunspot year, and the resemblance of the Quiet to the Weak jet day, and the Disturbed to the Strong jet day is readily seen.

(iii) It was thought worthwhile to examine the time-variations of $h_{max}F_2$, y_m, $N_{max}F_2$ and N_T for these sets of days, and these are shown in Fig. 6 (e)(Pg.166(a)). The $N_{max}F_2$ variations follow the course of the f_oF_2 variations with clear bite-out on strong jet days and reduced bite-out on weak jet days. The total electron content below the F_2 peak (N_T) variations however, show little difference between the strong and weak jet days in either month. This may be partially understood by studying the variations of $h_{max}F_2$ in August. F_2 peak heights are

much larger on a strong jet day than on a weak jet day; semi-thickness y_m follows the same variations as $h_{max}\ F_2$ showing that the whole layer expands and thickens on a strong electrojet day, while no such thing is seen on a weak jet day. Strong jet days seen to be associated with large peak heights and reduced electron densities, while weak jet days are associated with smaller heights and higher densities, so that N_T does not appreciably change between the two days. In December, it may be noted that the bite-out occurs earlier on the strong jet day, and is accompanied simultaneously by greater heights $h_{max}\ F_2$ and larger semi-thickness y_m. On a weak jet day, forenoon heights and semi-thickness are both smaller. In the afternoon hours when the bite-out ceases, the reverse is seen, with greater heights and a larger N_T on weak jet days. The behaviour of these parameters in December is slightly complicated and could do well with further investigation.

6.6 Electrojet effects on F_2 critical frequencies associated with geomagnetic storms.

Fig. 4 of the Paper shows the f_oF_2 variations on some typical International Quiet (Q) and Disturbed (D) days of the IGY-IGC period, together with the corresponding H variations. The Q days all show deep midday bite-out in f_oF_2 while the D days show hardly any bite-out.

This suggested a resemblance of Q days to strong jet days and D days to weak jet days, and in order to show this better, constant electron density contours for Q and D days were compared with similar contours for strong and weak jet days, both for high sunspot conditions (Fig. 9 of Paper). The resemblance between the two at all heights is seen.

Here we have studied some geomagnetic storms for the year 1964 as to how f_oF_2 changes at Ahmedabad (crest) and Kodaikanal (trough) from a day before the storm through 3 days after the storm when conditions are expected to return to normal. Three storms which depict the changes clearly are shown in Fig. 6(f) (Pg. 170(a)).In each block, the lower curve shows the variations of H at Trivandrum (equatorial), with the beginning and end of the storm marked on it and the maximum A_p attained during the course of the storm (this is a measure of the intensity of the storm) indicated too. The variations of f_oF_2 on the same days are shown above the H variations, those at Kodaikanal being indicated by a full line, and at Ahmedabad by a dashed line.

(i) Consider the storm of January 1964. On 1st (a control day) Ahmedabad frequencies are high, and some bite-out is seen at Kodaikanal, on 2nd both these features reduce, on 3rd there is no bite-out at

170(a)

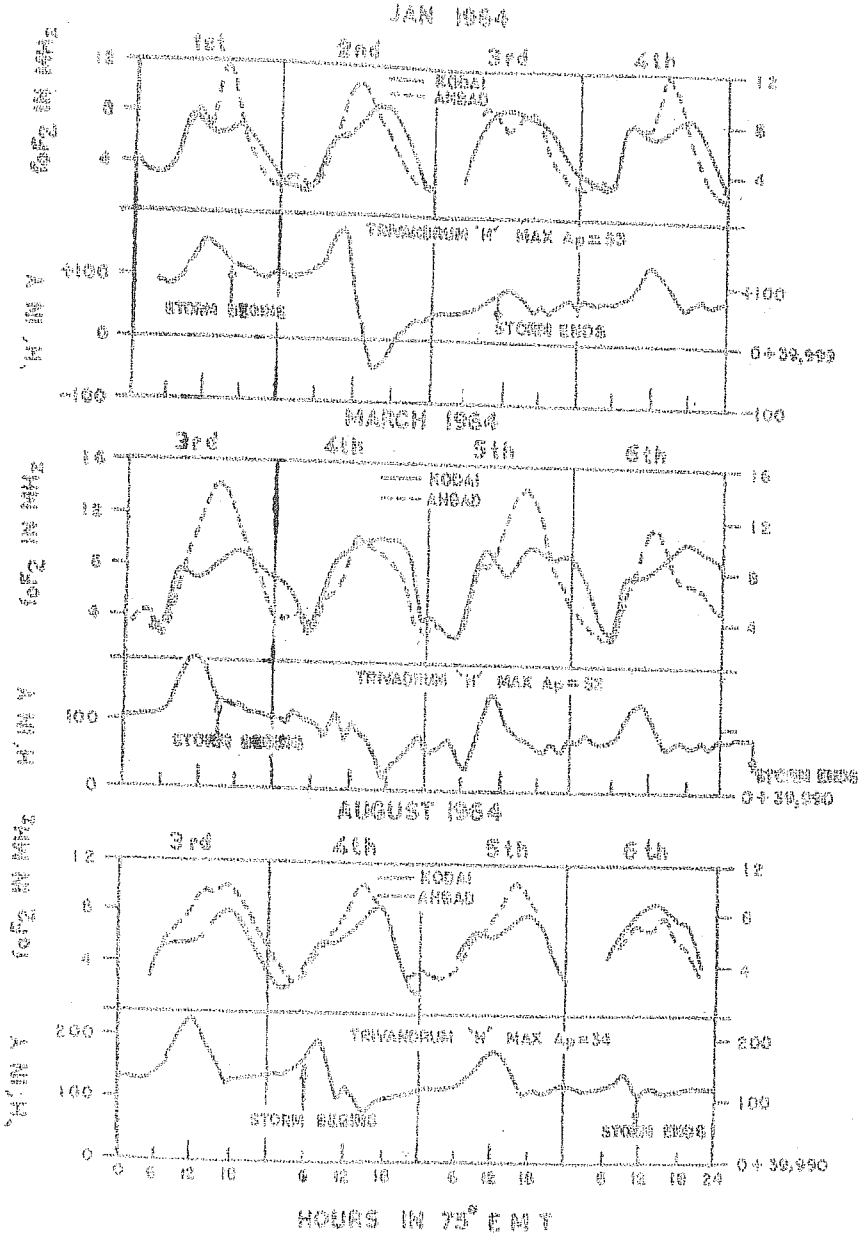

JAN 1964
1st
2nd
3rd
4th
TODAY
AHEAD
TRIVANDRUM 'H' MAX Ap=33
STORM BEGINS
MARCH 1964
3rd
4th
5th
6th
TRIVANDRUM 'H' MAX Ap=32
AUGUST 1964
TRIVANDRUM 'H' MAX Ap=34
HOURS IN 75° E M T

Fig 6.f

Kodaikanal, and the frequency here is higher than at Ahmedabad, which means that the equatorial F_2 anomaly has completely vanished. Some bite-out is seen at Ahmedabad on this day - it is an unusual feature and its cause is not known (Rastogi and Sanatani 1968). On the 4th normal conditions regain -the bite-out at Kodaikanal returns and Ahmedabad f_oF_2 increases.

(ii) Consider the storm of March 1964. On 3rd Kodaikanal exhibits a marked bite-out in f_oF_2 while Ahmedabad frequencies are high. On 4th the bite-out vanishes completely and Kodaikanal frequencies increase while Ahmedabad frequencies show a sharp drop below even Kodaikanal -once again the F_2 equatorial anomaly seems to have vanished. On 5th normal conditions are restored with bite-out at Kodaikanal and increased f_oF_2 at Ahmedabad. On 6th again Ahmedabad frequencies decrease and Kodaikanal frequencies increase slightly, but this may be associated with a weakening of electrojet by factors other than magnetic disturbances.

(iii) The storm of August 1964 is a weaker one and there is no effect till 5th August. On 3rd, 4th, 5th throughout, the f_oF_2 bite-out at Kodaikanal and enhanced frequencies at Ahmedabad are seen. On 6th the bite-out at Kodaikanal vanishes completely and Ahmedabad frequencies drop below

Kodaikanal — once again the equatorial anomaly has completely disappeared. This is also a day of very weak jet as can be seen from the H variation below.

All these f_oF_2 variations at crest and trough stations suggest a weakening of equatorial electric fields following a geomagnetic storm; how long after the storm commencement the weakening sets in, evidently varies from storm to storm. This is supported by drift observations at equatorial station Thumba, where the F-region horizontal drift is found to reverse from a Westward to an Eastward direction during the main phase of a storm(Misra (1971) Ph.D Thesis).

6.7 Electron density distributions at anomaly crest and trough for a geomagnetic storm

A similar effect of change in f_oF_2 at Ahmedabad and Kodaikanal is shown for a large s.c. storm in June 1965 together with the corresponding H variations in Fig. 5 of the paper. It was decided to work out the detailed electron density profiles at both Ahmedabad and Kodaikanal from the ionograms for these storm days - namely 15th, 16th, 17th June - to see how the ionisation pattern changes. The storm commenced at a late hour of the 15th, and so 15th was treated as a control day. The 16th represents the main phase of the storm while the recovery phase has started on the 17th.

(i) Electron densities at constant heights at Ahmedabad and Kodaikanal

These variations are shown for 15th, 16th and 17th June 1965at Kodaikanal (trough) and at Ahmedabad (crest) in Fig. 6 (g) (Pg.175(a)). On the control day (15th) a deep bite-out in $N_{max}\ F_2$ is seen at Kodaikanal, while $N_{max}\ F_2$ at Ahmedabad is very large with a peak value of (200×10^4) el/cm^3. During the main phase (16th) the amount of bite-out at Kodaikanal is considerably reduced and $N_{max}\ F_2$ has increased too; at Ahmedabad on the same day peak $N_{max}\ F_2$ has dropped sharply to (100×10^4) el/cm^3 and the shape of $N_{max}\ F_2$ is unusual with three peaks. When the recovery phase starts (17th), the bite-out almost vanishes at Kodaikanal and $N_{max}\ F_2$ increases considerably; at Ahmedabad, though peak $N_{max}\ F_2$ has risen to (140×10^4) el/cm^3, it is still below the normal level. Apparently the greatest effect of the storm at Ahmedabad is during the main phase on the 16th, while at Kodaikanal it is on the 17th during the recovery phase. The reason for this is not clear.

These electron density distributions suggest that with the onset of the geomagnetic storm, the forces which cause daytime F_2 bite-out at an equatorial station are reduced; the ionisation which

was being received by the crest station before the storm is reduced too. If we agree that the crest ionisation comes from that lost by the trough, the force which is reduced during storms is the vertical $\vec{E} \times \vec{B}$ lifting force, which can come about as a consequence of a weakening of $\vec{E}$, the electric field over the equator.

(ii) N-h profiles at Kodaikanal and Ahmedabad are compared for the 15th (control day) and 17th (storm day) in Fig. 6(h) (Pg. 175 (a)). These profiles are shown for every hour from 07 hr. to 18 hr. for heights ranging from 100 km to 550 km. The ordinate is the true height in Kilometers and the abscissa shows the electroh density in electrons/cm^3; The control-day profiles are depicted by full lines, and the storm-day profiles by dashed lines.

At the trough (Kodaikanal), the storm-day shows increased electron density at levels below the F_2 peak from 09 hr. to 12 hr., though there is a deficit in the topside as compared to the control day. From 13 hr. to 17 hr. the excess ionisation extends to the top too on the storm-day, and is found at all levels, both bottom-side and topside. By 18 hr. the excess remains at the topside, but a deficit starts in the bottomside on the storm-day.

At the crest (Ahmedabad) a slight excess in ionisation on the storm-day is seen at levels from 100 km to 250 km from 10 hr. to 16 hr., but at higher levels, near the F_2 peak and above in the topside, there is a great deficit of ionisation. This is in direct contrast to the excess ionisation seen at Kodaikanal on the storm-day. Only at 17 hr. and 18 hr. does the topside deficit start reducing ; the deficit at the F_2 peak however remains.

The profiles suggest that at levels near the F_2 peak there is a large excess of ionisation at the equator on the storm-day while the crest stations shows a large deficit on the same day. These N-h profiles in Fig. 6(h) (Pg.175 (a)) at Kodaikanal show a great resemblance to the N-h profiles at Kodaikanal shown in Fig. 6 (d) (Pg.166 (a)) the storm-day profile resembling that on the weak electrojet day, and the control day profile resembling the strong electrojet day. This suggests a weakening of the $\overrightarrow{E} \times \overrightarrow{B}$ force over the equator during a storm day which results in increased ionisation at the equator and reduced ionisation at the anomaly crest.

(iii) The variations in the parameters $h_{max}\ F_2$, y_m $N_{max}\ F_2$ and N_T for the control day (15th) and the storm day (17 th) at Kodaikanal and Ahmedabad are shown

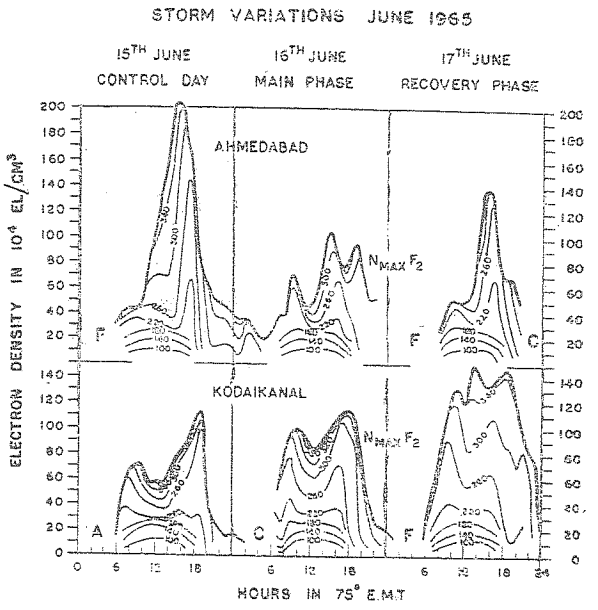


Fig. 6.g

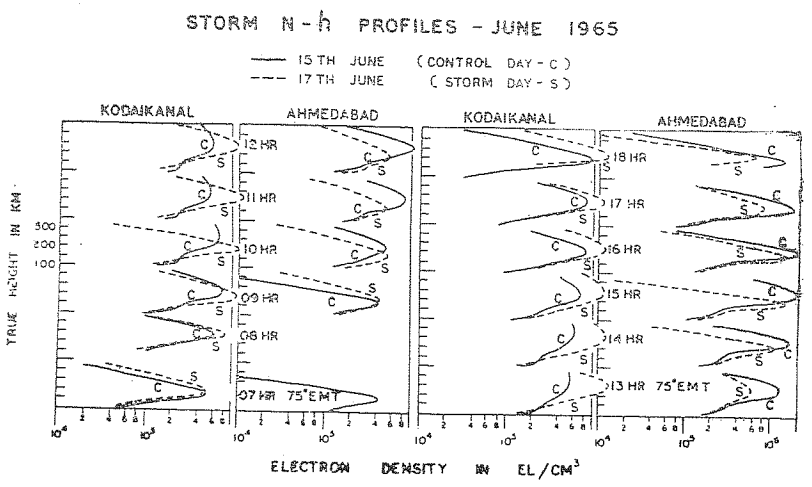


Fig. 6.h

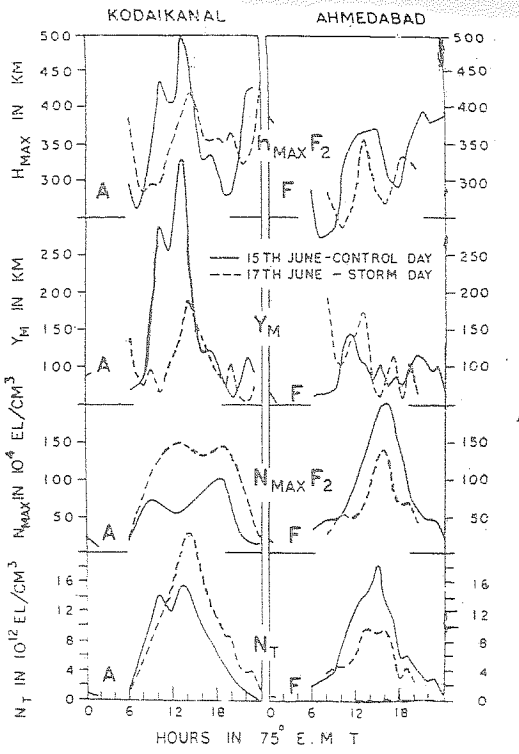


Fig. 6.i

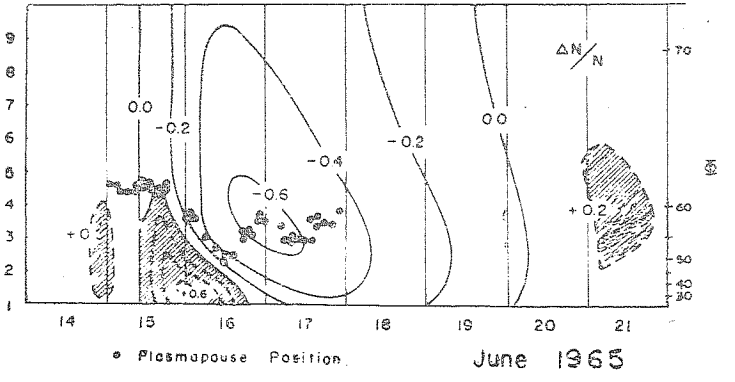


Fig. 6.j
Contour map fo △N/N and position of plasmapause in L-value versus time. (Obayashi 1971)

175(a)

in Fig. 6 (i) (Pg. 175(a)) and are quite interesting. The most striking features are seen in N_{max} and N_T. On a storm day (dashed lines) the daytime bite-out in N_{max} F_2 seen on the control day (full lines) is greatly reduced at Kodaikanal; Correspondingly N_T, the total electron content up to the F_2 peak is greatly enhanced on a storm-day. At the crest station Ahmedabad however, the reverse is seen with reduced N_{max} F_2 on the storm-day and greatly reduced N_T. It seems reasonable that on the storm-day there is reduced transport of ionisation from the anomaly trough to the crest, since both N_{max} and N_T increase at the former and decrease at the latter. This could very well be associated with decreased $\vec{E} \times \vec{B}$ vertical uplift at the equator, and hence reduced electric fields during storms.

F_2 peak heights seen reduced at most hours on the storm day at Ahmedabad. At Kodaikanal the decrease in height is seen only in the forenoon hours, and is associated with increased N_{max} F_2 at those hours; in the afternoon, storm day heights are more than control day heights and N_{max} and N_T too remain larger. The observed increase in equatorial N_{max} F_2 has thus nothing to do with the different recombination rates associated with variations in the F_2 peak level. The variations in y_m at Kodaikanal

are in sympathy with those of $h_{max}\ F_2$, with increased forenoon layer thickness and little change in afternoon semi-thickness. The variations in y_m at Ahmedabad do not show any clear trend.

It is interesting to note that Obayashi (1971; private communication) has studied the same storm of June 15th - June 21st for stations located all over the world and situated above $30^\circ \phi_c$ (corrected geomagnetic latitude). $\Delta N_M/N$ at the F_2 peak level is studied from both ground-based sounders and topside sounders, and is depicted along with the L-value of the plasmapause as inferred from whistler data (Fig 6 (j) (Pg. 175 (a)). It can be seen that the plasmapause moves in from a value of L = 4.5 on 15th to a value of L = 2.3 on 16th Enhancement of electron density is seen at locations above $30^\circ \phi_c$ on the 15th and 16th , and a decrease is seen in the later stages of the storm. The variations below $30^\circ \phi_c$ are possibly extrapolated, and show the same. We see however from the results in this Chapter that a decrease in electron density occurs at Ahmedabad (+ $14^\circ.1$ geomagnetic latitude) from 16th June itself, though Kodaikanal (+ $0^\circ.7$ geomagnetic latitude) at equatorial latitudes does show an enhancement on 15th, 16th and 17th June. This suggests that the observed decrease at Ahmedabad is associated with factors other

than the neutral winds across the plasmasphere by which Obayashi explains the electron density enhancement of 15th and 16th at latitudes above $30^{\circ} \phi_c$.

6.8 Conclusions

From these studies of f_oF_2 and electron density distributions at an anomaly trough and crest station, we deduce the following -

(1) Daytime f_oF_2 at both anomaly trough and crest station are related to the strength of the equatorial electrojet as inferred from the daily range of H. This relationship holds better for magnetically quiet conditions than for disturbed conditions.

(2) Weak electrojet days at the equator are associated with smaller F_2 peak heights and larger ionisation at the bottomside as compared to strong electrojet days.

(3) Following a geomagnetic storm, ionisation at the F_2 peak level and above increases at a trough station, while it decreases at a crest station. Following a storm both $N_{max}\ F_2$ and N_T increase at the trough and decrease at the crest. This is very likely a result of the weakening of equatorial electrostatic fields during storm-conditions, with a consequent reduction in the $\vec{E} \times \vec{B}$ uplifting force.

CHAPTER - VII

CONCLUSIONS

From the behaviour of the magnetically - disturbed F-region which has been illustrated and discussed in the preceding chapters, the outstanding points can be separated out, and an attempt made to investigate their causes. We can first look into the already-existing ideas on the causes of ionospheric storms.

7.1 Current ideas on F-region ionospheric storm mechanisms.

Most efforts to explain F-region ionospheric storms have revolved around two main effects.

(a) The effect of electrodynamic drifts brought about by storm-time currents.

(b) Heating effects during storms which bring about photochemical changes, altered reaction rates, and affect thermospheric wind patterns.

(a) Electrodynamic drift effects - are believed to arise from the interaction of the geomagnetic field with the electric fields set up during storms.

This effect was advocated strongly by Martyn (1953) and developed by the Japanese group (Maeda 1955; Hirono 1955; Sato 1957). Maeda and Sato (1959) substituted

estimated drift velocities and assumed electron production and loss rates, into the continuity equation, and solve it to get results for DS variations in mid and low latitudes which did not differ too much from observed values. The drawback however is, that they did not take diffusion into account, and the height distribution of loss rate assumed by them differs from what has recently been obtained from observations. Rishbeth (1963) obtained results for mid-latitudes in support of the drift theory. A drawback of the drift theory is that it cannot explain decrease of electron density accompanied by increase in height, as is often observed during storms.

(b) Thermal effects

Satellite data points to evidence that upper atmospheric temperatures increase substantially during storms (Jacchia 1961; Groves 1961) (References in Ch. 3) Yonezawa (1963) showed that the rate of electron loss in the F-region is enhanced by a temperature increase and explains reduced electron density at mid and higher latitudes. The equatorial and low-latitude increase of electron density was explained by Yonezawa in 1962 (Obayashi 1964) taking an inverse temperature-dependence of the radiative recombination process for the heights 400-500 km of the h_{max} F_2 level obtained at the equator.

This is not a very satisfactory approach. Matuura (1963) too from a study of N-h profiles showed that electron loss and diffusion rates change appreciably with temperature.

The effect of temperature changes in bringing about dynamical motion in the F-region has been another avenue of study. Nagata (1954) suggested that thermal expansion of the atmosphere due to particle bombardment can reduce F-region electron densities at high latitudes. Reddy et al., (1967) used the same reasoning to account for enhanced electron densities observed in the topside ionosphere at high latitudes during storms. Seaton (1956) suggested that enhanced mixing in the F-region during storms would alter the concentration of neutral O_2 molecules, and thus alter charge-exchange processes. Rothwell(1963) suggested increased diffusion during storms from the summer to the winter hemisphere. Thermospheric neutral winds set up by storm-heating in high latitudes are considered by Cole (1962 a) and J.W. King (1970); Duncan (1969) has advocated the effect of global atmospheric circulation induced by storm heating.

Rishbeth (1968) has given an intensive review of the possible effects which could influence storm time F-region behaviour. None of these is, however, capable of explaining the F_2 region storm behaviour at all latitudes.

On the basis of the results in this Thesis, it is felt that while all these factors discussed above do come into play during magnetic storms, they affect the different latitudes of the earth in different measure, depending on the degree of geographic and geomagnetic control at the latitude concerned. One can evaluate the importance of the various processes at different latitudes required to satisfy the observed behaviour of the disturbed F_2-region.

7.2 Outstanding features of disturbed F_2-region behaviour.

From the results presented in this Thesis, we find that magnetic disturbances have a tendency to level out most anomalies of the Quiet F-region. Generally speaking

(a) They fill up the equatorial anomaly trough (Ch. 5 and Ch. 6)

(b) They fill up the trough between the winter spur and the anomaly crest in the winter hemisphere (Ch. 5) and the winter spur is less pronounced on disturbed days. The spur in the summer hemisphere in the night is reduced by disturbances (Ch. 5).

(c) The post-sunset rise in $h_{max}F_2$ at equatorial stations (most marked in high sunspot years) is less on Disturbed days than on Quiet days. This is seen from the electron density profile studies in Ch. 4.

(d) The post-sunset rise in f_oF_2 at stations of 31° dip (most marked in high sunspot years) is less on Disturbed days than on Quiet days (Ch. 4). This feature could well be related to observation(c).

(e) The decrease of daytime f_oF_2 below night-time f_oF_2 seen in the southern hemisphere high latitude stations is less on Disturbed days than on Quiet days (Ch. 4).

All these points suggest in a general way that the electric fields in the ionosphere, and the neutral winds in the thermosphere set up during disturbed conditions are such as to modify the same during quiet-time conditions.

The studies of Ch. 4 and Ch. 5 show that it is the mid-latitudes which show the greatest dependence of disturbance effects on season, time of commencement of storm, north-south asymmetry etc. The higher and lower latitudes do not show the drastic change in phase of disturbance displayed by the mid-latitudes. The intensity

of F_2 region disturbance is more in the 75°W zone than in the 75°E zone, showing that the geomagnetic field plays a decisive role in storm-effects.

7.3 Electric fields and thermospheric wind systems associated with magnetically disturbed conditions

At this stage it is worthwhile to consider some of the effects which accompany magnetic storms. Broadly speaking, storms set up electric fields which drive electric currents in the ionosphere; the heating associated with the latter sets up thermal and pressure gradients which give rise to thermospheric wind patterns. These winds are in turn associated with ion-drag effects, air-convection currents, increased turbulence and mixing (G.A.M. King 1966) etc. A good review of these effects accompanying storms has been given by Cole (1966).

1. Electric fields

Electric fields in the magnetosphere can be generated in several ways:

(a) Viscous interaction between the solar wind and the magnetospheric boundary, and subsequent convection of plasma within the magnetosphere, has been suggested by Axford and Hines (1961) and Piddington (1964). They believe that it can occur even during quiet conditions,

but is greatly enhanced during storms.

(b) Field-line reconnection in which the earth's field lines join up with the interplanetary field lines directed southwards at disturbed times was suggested by Dungey (1961). An electric current is generated at the neutral point on the night-side, and gives rise to a plasma flow directed outwards in all directions from the null-point. An electric field given by

$$\vec{E} + \vec{V} \times \vec{B} = 0$$

is associated with this plasma flow, and is communicated to the high latitude regions along the equipotential geomagnetic field lines. In this model, the solar wind is believed to vary in strength with solar activity. As the wind increases, the rate of recombination of the field lines in the nightside increases, and the disturbances associated with high latitudes extend to lower latitudes. Such field line reconnection has been discussed by Sonnerup (1965), and evidence of a southward directed interplanetary field at times of polar magnetic substorms has been obtained from satellite studies by Fairfield and Cahill (1966) and Rostoker and Fälthammar (1967)

(c) Charge-separation - Chamberlain (1961, 1962) suggested that following auroral acceleration, a drift of ions and electrons in opposite directions due to

gradient in geomagnetic field, provides the electric field to drive the auroral electrojet. Kern (1961, 1962) said azimuthal gradients in the distorted geomagnetic field would effect change-separation of drifting particles. Fejer(1961) suggested that charge separation too could lead to the type of convection patterns suggested by Axford and Hines (1961).

Whichever the mechanism, there must be a continuous input of energy from outside to supply the energy of auroral and magnetic storms, as these electric fields are heavily dissipated in the ionosphere. Such a source of energy is the solar wind. Another means of sustenance of the particle energy is the geomagnetic field itself. In order to conserve the adiabatic invariant μ in

$$\mu = \frac{1/2\ mV^2}{B}$$

when a particle is accelerated from the neutral point where B is quite small, towards the earth where B is large, V has to increase tremendously. It gains this energy at the expense of the magnetic field.

The mechanisms by which such electric fields generated in the magnetosphere are applied to the ionosphere, at times of storms as suggested by various workers are discussed by Aggson (1969).

Bostrom (1967) suggested electric fields driving the electrojet within an auroral arc, with a small return current to the magnetosphere. In the Axford and Hines (1961) model, as in most models, the electric fields are mapped down into the ionosphere along the equipotential geomagnetic field lines.

(2) Heating effects during magnetic storms

(a) The Joule dissipation of ionospheric currents (both Sq and auroral electrojet) is believed to be an important heat source (Cole 1963 a; Kato 1962; Krassovsky 1959; Moe 1963) Joule heating of the S_q current system was first suggested by Schuster (Chapman 1937). The steady state current is given by

$$j = j_{\parallel} + j_{\perp}$$

$j_{\parallel}$ - component parallel to geomagnetic field B

$j_{\perp}$ - component perpendicular to B

The Joule dissipation is given by

$$Q = j \cdot E = \sigma_0 E_{11}^2 + \sigma_1 E_{\perp}^2$$

where σ_0 - conductivity parallel to B,

σ_1 - Pedersen conductivity

Cole (1971 b) gives the value of Q as

$Q = 7 \times 10^{-4} (\Delta H)^2$ ergs/cm^2 sec. by night and

$Q = 7 \times 10^{-5} (\Delta H)^2$ ergs/cm^2 sec by day

where ΔH - magnetic disturbance at ground in gammas.

(b) Stable auroral red arc heating

Cole (1965) believes that at mid-latitudes, ring current particles yield their energy to background thermal plasma of the magnetosphere through Coulomb collisions. This heat is conducted into the F-region of the ionosphere to raise the electron temperature T_e, sufficient to excite atomic oxygen to the ^1D state. This causes the red arc at latitudes slightly equatorwards of the normal auroral activity belt. This region of enhanced T_e slightly above the plasmapause has been noticed by satellites (Findlay and Cole 1970).

(c) Heating by corpuscular bombardment

Not many calculations on this exist, though it could be of significance. Chamberlain (1961), feels that 5% to 10% of the energy of energetic electrons involved in aurorae goes towards heating of the ionosphere.

(3) Wind systems associated with storms

Electric fields orthogonal to the geomagnetic field

(a) give rise to the Lorentz force $\vec{j} \times \vec{B}$ causing thermospheric motion

(b) give rise to Joule dissipation of heat.

These cause winds (Cole 1962 a); a typical wind-speed in the E-region at night is calculated by Cole (1971) as

$$V^2 = \frac{7 \times 10^{-4} L_e (\Delta H)^2 T_E}{ML_s}$$

Where

M = mass of atmosphere subject to Joule heating

L_e = latitude thickness of auroral electrojet heating region

L = latitude thickness of convection cell about the electrojet

ΔH = magnetic disturbance observed at ground

T_E = time for which electric field acts

and has values of upto 500m/sec for $\Delta H = 1500$ gammas.

As a consequence of Joule heating, the pressure gradient at a given height was given by Cole (1962 a) as

$$\nabla P = jH$$

where ∇P = pressure gradient

j = current density

H = scale height

Such enhancements of pressure at large heights have been detected over the auroral zone by satellites (Jacchia and Slowey 1967).

(c) Obayashi (1971) feels that the compression of the plasma-sphere during magnetic storms as inferred from Whistler studies can give rise to enhanced temperature and pressure within it. This sets up gradients resulting in thermospheric wind systems at mid-latitudes across the plasmapause

Having established the presence of electric fields during storms with their associated heating, pressure gradient, and thermospheric wind effects, we can proceed to see how these features fit in with our observations of F_2-region storms.

7.4 Disturbed F_2 behaviour in High Sunspot years

During equinoxes the disturbance effects are fairly symmetrical about the equator with an increase in f_oF_2 between $\pm 30^\circ$ dip and a decrease beyond. During the solstices the maximum increase of f_oF_2 is at the winter mid-latitudes centred around 60° dip and exists between 40° and 70° dip. There seems to be a slight decrease of f_oF_2 around 30° dip, (the region of the anomaly crest) in the winter hemisphere and at 30° dip and beyond in the summer hemisphere. There is a decrease of f_oF_2 in all seasons during disturbances at the high latitudes, but the greatest decrease takes place in the summer high latitudes as compared to the winter high latitudes. These features have been illustrated in Ch. 5. They are discussed in Paper (see overleaf) together with the possible mechanisms which could be causing them.

The conclusions of this paper can be summarised thus.

The continuity equation for the F-region,

$$\frac{\partial N}{\partial t} = Q - L - \text{div}\,(Nv)$$

suggests that any changes in electron density distribution with time, $\partial N/\partial t$, could be due to changes in the production Q, loss L, or transport div (Nv). Changes in Q and L can be brought about by

Ann. Géophys., t. 27, fasc. 4, 1971, p. 666 à 666.

Ionospheric F-Region disturbances and their possible mechanisms

by Mrs Girija RAJARAM, A. C. DAS and R. G. RASTOGI,

Physical Research Laboratory,
Ahmedabad-9, India.

ABSTRACT. — *A global study of F region disturbance effects shows that the largest enhancement of storm f_0F_2 relative to quiet f_0F_2, occurs in the mid-latitudes of the winter hemisphere centred around 50° dip, and is larger than the equatorial f_0F_2 enhancement. In the equinoxes, the classical ideas regarding the increase in equatorial f_0F_2 during disturbances hold good, as also the high-latitude decrease of disturbed f_0F_2 in all seasons. An attempt is made to explain these observations on the basis of neutral winds, electrodynamic drift effects, and temperature and chemical composition changes during magnetic disturbances.*

Paper 9

1

The effect of magnetic storms on the critical frequency of the $F2$ layer (f_0F_2) at different latitudes has been studied by various workers. In general, it is found that during disturbances f_0F_2 increases at low geomagnetic latitudes, and decreases at high geomagnetic latitudes in all seasons, while at mid-latitude stations, f_0F_2 shows a seasonal change-over with an increase in winter, and a decrease in summer [APPLETON et al 1937; BERKNER and SEATON 1940; MARTYN 1953; MATSUSHITA 1959; MAEDA and SATO 1959].

The present work describes some new features observed from a study of ionospheric storms individually at a large number of stations ranging from 83° dip north to 83° dip south; most studies so far have grouped stations into different geomagnetic latitude zones. The period of study is the high solar activity IGY-IGC, and the disturbance effects have been computed separately for the 3 seasons, *D*-months (November, December, January, February), *E*-months (March, April, September, October) and *J*-months (May, June, July, August).

The storm-effects have been studied in two ways. Firstly by considering the universal time component D_u (f_0F_2) i.e. the ratio storm-time f_0F_2/median f_0F_2 for the corresponding hour, starting from the hour of commencement of the magnetic storm. Such an index averaged over the first 48 hours of the storm for a large number of storms is denoted by D_m (f_0F_2), and is shown in Fig. 1; secondly, by considering the local solar time effects for specified times (the midday hours (10-14) and midnight hours (22-02) have been chosen here) on International Disturbed Days (*D*) and International Quiet Days (*Q*). Fig 2 shows the latitudinal variation of these ratios for each season of the IGY-IGC period, together with the corresponding latitudinal variation of all-day average f_0F_2.

Referring to Fig. 1, during *E*-months, the increase of f_0F_2 during disturbances occurs within ± 30° dip, beyond which D_m (f_0F_2) decreases continuously with increasing dip angle. This behaviour is similar to the curve obtained by Appleton and Piggott [1955]. During the *D*-months (northern winter), a definite "hump" in D_m (f_0F_2) is seen between dip 50° ± 10° north. During the *J*-months (southern winter), a similar „hump" in D_m (f_0F_2) is seen around 50° dip south. The outstanding feature is that the increase of f_0F_2 at the mid-latitudes of the winter hemisphere is nearly 10 %, while the maximum increase of equatorial f_0F_2, even in the *E*-months, is only 5 %. Thus it is not a shift in latitude of the equatorial peak towards the mid-latitudes of the winter hemisphere, but a definite change occurring here due to some different cause. The "humps" centred around 50 °N and 50 °S dip are much larger than the corresponding equatorial enhancement of disturbed f_0F_2, showing that the peak effect of magnetic storms on the *F*-region occurs at the mid-latitudes of the winter hemisphere.

2

In Fig. 2, the regions where f_0F_2 is greater on *D* than on *Q* days are shaded. During the *E*-months, the latitudinal variation of the daytime D/Q (f_0F_2) curve is fairly symmetrical about the equator, with the ratio greater than 1.00 within ± 40° dip, and the ratio decreasing gradually with increasing dip beyond. This zone of enhanced f_0F_2 during disturbances coincides fairly well with the zone within the two f_0F_2 crests of the Appleton anomaly in the latitudinal variation of average f_0F_2. In the night hours, the region of enhanced f_0F_2 is narrower (within ± 30° dip) but the enhancement is of greater magnitude. It is interesting to note that the equatorial anomaly in f_0F_2 itself is stronger in high sunspot years and narrower at night. This suggests that in the *E*-months, F_2-region ionospheric disturbances are closely associated with the equatorial anomaly, and magnetic disturbances tend to fill up the equatorial trough of f_0F_2.

During the *J*-months, the D/Q (f_0F_2) curve for the daytime hours shows that in the northern (summer) hemisphere, the ratio falls off gradually from a value of over 1.00 at the equator, through 1.00 at 30° dip, to a value of about 0.80 near the poles. In the southern (winter) hemisphere, after a short decrease within 0° and 20 °S dip, there is a large "hump" centred around 40 °S dip; a decrease of f_0F_2 during *D* days is shown only at dip greater than 75 °S. Comparing the D/Q (f_0F_2) curve with the average f_0F_2 curve, it is seen that in the latter, in the summer hemisphere, f_0F_2 decreases with increasing dip beyond the anomaly crest, while in the winter hemisphere, a secondary peak known as the winter 'spur' is noticed around 60° dip [CROOM et al 1960; J. O. THOMAS 1964]. During the night hours there is no equatorial enhancement of D/Q (f_0F_2) but a very strong peak is seen around 60 °S dip with a peak value of about 1.20. The 'spur' in the average f_0F_2 curve, however, disappears at night.

3

During the *D*-months, the daytime ratio D/Q (f_0F_2) is uncertain at equatorial latitudes; this is due to longitudinal differences in ionospheric disturbances [RASTOGI and RAJARAM, 1965]. There is a minor peak at 40 °S, and a definite peak around 50 °N dip (winter mid-latitude). The corresponding latitudinal variation of average f_0F_2 shows a small hump at winter high-latitudes, which is the winter "spur" (7). The night-time ratio of D/Q (f_0F_2) indicates that the "hump" in the northern hemisphere has shifted polewards and it now has its peak at 60 °N dip; also, the magnitude of the "hump" is greater. There is a clear equatorial enhancement of the D/Q (f_0F_2) ratio between ± 20° dip corresponding to the region between the crests of the F_2 anomaly. In the average f_0F_2 curve, the winter "spur" seen in the daytime at 60 °N has completely vanished at night.

Summarising, the effect of magnetic disturbances on the F_2 layer is to increase f_0F_2 in the equatorial and low-latitude regions, markedly so in the equinoxes. The mid-latitudes show a seasonal variation with disturbed f_0F_2 being decreased in summer, but increased in winter; the winter mid-latitude increase is larger than the equatorial increase of disturbed f_0F_2. The high-latitudes always show a decrease of f_0F_2 irrespective of the season. An attempt is made here to explain these observations qualitatively.

DISCUSSION

The behaviour of the *F*-region, even during quiet conditions, has been difficult to explain because *F*-region ionisation is controlled by transport effects, apart from simple production and loss processes. Review articles on F_2 layer behaviour are given by Martyn [1959], Ratcliffe [1956] and Rishbeth [1967], while the physical processes which could cause the observed phenomena are discussed by Rishbeth [1968].

The *F*-region behaviour during disturbed conditions is even more complicated as disturbances introduce distortions in the normal factors which account for its behaviour. Such disturbances cause thermal heating of the upper atmosphere, thereby changing ionisation and recombination rate coefficients, setting up pressure gradients and thermospheric winds, and bringing

about composition changes by increased turbulence and mixing. Additional current systems in the upper atmosphere are set up by the entry of charged particles, and these can drastically change the electromagnetic drift patterns $\vec{E} \times \vec{B}$ all over the earth. Earlier workers have considered some of these possibilities in attempts to explain *F*-region storm-behaviour, but the combined effects of these over the complete range of latitudes have not yet been considered. The present authors believe that all these factors come into play during ionospheric storms; however, they affect the different latitudes of the earth in different measure, depending on the degree of geographic and geomagnetic control at the latitude concerned.

For equinoctial conditions during disturbed days, the increase of f_0F_2 near the equatorial region, and a decrease beyond, could be due to the combined effect of electrodynamic drift and neutral winds. One can first consider how the electrodynamic drift plays an important role. During the main phase of a storm, a half ring current is produced on the night side of the magnetosphere [PIDDINGTON 1967]. The exact trajectory calculation in the equatorial plane of the magnetosphere shows that the electrons drift towards the east while the protons drift towards the west. The forbidden region for electrons and protons are different [KAVANAGH et al 1968]. These produce space charges which follow the magnetic field lines to reach the ionosphere around 50° geomagnetic latitude. A polarised electro-static field is produced which is in a direction opposite to that of the ambient S_q electric field.

The electric field will thus be reduced during the disturbed days and it should manifest itself in reducing both the electrojet current and the upward electrodynamic drift near the equator. As a result one would expect reduced upward drift of electrons at the equator, with increased values of f_0F_2 and less F_2 midday biteout. This is observed to be so, for the effect of magnetic disturbances is to fill up the Appleton anomaly trough in f_0F_2.

The influence of the horizontal neutral wind on the motion of plasma in the *F*-region is discussed by Dougherty [1961]. Following Jacchia's model [1965], a thermospheric wind can be generated above 110 km at the equator and move towards the poles. This wind will have both north-south and east-west components. The general wind pattern during the equinoxes and quiet days has been discussed by Kohl and King [1967] and Strobel and McElroy [1970]. In the northern hemisphere it is northward during day and southwards at night. Neglecting terms of order ν_i/Ω_i where ν_i is the collision frequency and Ω_i is the gyrofrequency, to a first approximation, the motion of charged particles can be represented by :

$$u = u_e = u_i = U\cos^2 I - \frac{e}{m_i\nu_i} E_p \sin I \cos I \qquad (1)$$

$$v = v_e = v_i = 0 \qquad (2)$$

$$w = w_e = w_i = w_d - \frac{e}{m_i\nu_i} E_p \sin^2 I \qquad (3)$$

where

$$w_d = U \sin I \cos I$$

and

$$E_p = \frac{2K}{N_e}\frac{d}{dz}(NT) + m_i g$$

N is the number density for both electrons and ions, U is the wind velocity component in the north-south direction and is positive when southwards. m_i, T, g, K, and 'e' are the mass of the ion, temperature, the gravitational constant, the Boltzmann constant, and the charge of the electron respectively. u, v and w are the north-south, east-west and vertical components of the velocities of a charged particle, I is the dip angle, positive in the northern hemisphere. These equations are, however, not valid in the region very near to the equator because it has been assumed that $\sin I \gg \nu_i/\Omega_i$. East-West motion is negligible because the magnetic field effect is dominant over collisions in the *F*-region. The velocity components 'u' and w are strongly dependent on I. The wind effect on the vertical motion of a charged particle is maximum at $I = 45°$. The direction and magnitude of the wind are important in determining the direction and magnitude of the velocity of a particle.

For quiet-time equinoctial conditions, the thermospheric wind is $-U$ (predominantly from the equator to the pole), and assuming [DOUGHERTY]

$$U \approx \frac{e}{m_i\nu_i} E_p,$$

equation (1) becomes

$$u = u_e = u_i = -U\cos I(\cos I + \sin I)$$

and equation (3) becomes

$$w = w_e = w_i = -U\sin I(\cos I + \sin I)$$

The variation of u/U and w/U are shown in the left-hand side of Fig. 3. It can be seen that the velocity components of a charged particle are northwards and downwards for all dip angles. The northward component is greatest near the equator and low latitudes, and decreases towards the poles; the downward component increases from the equator towards the high latitudes.

During disturbed conditions, high and mid-latitude regions are heated up because of Joule heating [JACCHIA, 1961; GROVES, 1961] and the magnetic mirror heating due to electromagnetic disturbances in the magnetosphere. The thermospheric wind is then $+U$ (predominantly from the higher latitudes towards the equator) and with the assumption

$$U \approx \frac{e}{m_i\nu_i} E_p$$

equation (1) becomes

$$u = u_e = u_i = U\cos I(\cos I - \sin I)$$

and equation (3) becomes

$$w = w_e = w_i = U\sin I(\cos I - \sin I)$$

7

The variation of u/U and w/U with dip during these disturbed conditions are depicted in the right-hand side of Fig. 3, and are seen to differ considerably from the variations during quiet conditions. At low latitudes, 'u' is positive from $> 0°$ to 45° dip, showing that the charged particle has a southward velocity component in this region; beyond 45°, till 90° dip, 'u' is negative, indicating a northward velocity component. The vertical velocity component 'w' between $> 0°$ and 45° is positive i.e. upwards. Hence the downward motion of particles is inhibited, and they are not allowed to come to the lower region sink where the loss rate is high. This explains the low-latitude increase of f_0F_2 during disturbed conditions. Beyond 45° till 90° dip the vertical component 'w' remains negative i.e. it remains downwards and charged particles are driven into regions of greater loss. This explains the decrease of f_0F_2 observed at mid and high latitudes during the equinoxes.

It is possible that both these wind systems may be in operation simultaneously i.e. one wind system is from the high-latitudes to the mid-latitudes, while the other is from the equator to the mid-latitudes. The effect on the velocity components of charged particles, of these two wind systems would be an additive one, dependent on their relative magnitudes. There could be a small peak at the mid-latitudes which may be too small to be observed.

During the solstices the wind pattern described above changes. In the summer hemisphere it starts at mid-latitudes around 23° (geographic latitude) and then blows towards the poles. Thus it carries many particles, both neutral and charged, from the summer hemisphere towards the winter hemisphere. The counter wind starting from the pole will have the opposite effect discussed above.

The winter peak in D/Q (f_0F_2) shown in Fig. 1 and Fig. 2 can be explained as the combined effect of changes in the atmospheric composition, the recombination processes and the neutral wind. The changes in recombination rate β, and the ratio concentration n (O)/n (N_2) between summer and winter have been employed to explain the seasonal anomaly in the quiet F-region by Rishbeth and Setty [1961] and the storm-time behaviour of f_0F_2 by Seaton [1956] and L. Thomas [1970].

8

In the F-region, the atmospheric composition is predominantly atomic oxygen O, molecular oxygen O_2, and a small amount of molecular nitrogen Nt. Production of electrons is mainly by the ionizing action of the He I (584 Å) and He II (304 Å) spectral lines on the O atoms. Loss is mainly through the chemical reactions :

$$O^+ + O_2 \rightarrow O_2^+ + O \qquad (4)$$

$$O^+ + N_2 \rightarrow NO^+ + N \qquad (5)$$

resulting in the formation of the positive ions O_2^+ and NO$^+$. The free electrons are lost by dissociative recombination with these positive ions. This loss rate of ionization is observed to be higher in summer than in winter (Rishbeth and Setty 1961). The recombination coefficient β has been found to be 2-3 times greater in summer than in winter by several workers (Polyakov 1963; Nisbet and Quinn 1961; Bergh 1962), typical values being

	Summer	*Winter*	
β	$\sim 3 \times 10^{-4}$/sec	1.8×10^{-4}/sec	[Rishbeth and Setty]

This could be due to a seasonal variation in the vibrational temperature of N_2, being higher in summer and lower in winter. The rate coefficient for the reaction (5) has been found to be sensitive to the vibrational temperature of N_2 [Schmeltekopf et al, 1967].

The ratios $n(O)/n(O_2)$ and $n(O)/n(N_2)$ also increase during winter by a factor of almost two as compared to those during summer, typical values being :

	Summer	*Winter*	
At 350 Km O/N_2	6.9	12.2	[Waldteufel, 1970]

This is supported by recent mass spectrometric data [Krankowsky et al, 1968]. As a result more ionisation is observed in winter as shown by Strobel and McElroy [1970]. The prominence of the peak in the winter hemisphere during disturbed days can then be explained in terms of the neutral wind which is believed to be responsible for the increased winter

9

ratio O/N_2 and O/O_2. It has already been described above how these winds can produce peaks at mid-latitudes. A small peak in the summer hemisphere may also be expected but because of the decreased atomic O amount and the rapid loss rate as compared to the winter it will not be prominent enough to be seen.

There may be a magnetospheric effect on the winter mid-latitude f_0F_2 peak but this has not been studied in detail. It may arise from the asymmetric configuration of the magnetosphere during the solstices. The winter-summer asymmetry in geomagnetic activity has been discussed by Wulf [1971]. The motion of plasma or field lines at the polar regions of the summer hemisphere will be more than those during winter. This may increase the auroral current density which can extend to lower latitudes during disturbances. In the summer hemisphere the mirror heights of charged particles will then be increased by a couple of hundred kilometres and the increase in current density also increases thermal heating of the atmosphere. The combined effect is to reduce the particle precipitation effect and to enhance the recombination rate, thereby reducing the observed electron density. The current density will be small in the winter hemisphere, because of the slower flow of plasma in the polar region. Therefore the magnetic mirror heights will not be raised, and the effect of particle precipitation at lower heights will be dominant. As a consequence of this a large electron density could be obtained. This is, of course, highly qualitative but plausible. Furthermore, there is asymmetry of low energetic particle flux observed during summer and winter (Duncan, 1962; Maehlum, 1968) which may also contribute to asymmetry in the electron density at F_2 layer heights.

Very low values of f_0F_2 during the disturbed days at the latitudes above the auroral region can be understood in a simple way. During the disturbed days the motion of plasma or field lines near the polar region is very rapid and it is towards the night side of the magnetosphere. Thus the charged particles are removed from the higher F_2 region towards the tail of the magnetosphere. This resembles the polar wind, an important process in the top-side polar ionosphere. It has been shown by Banks and Holzer [1968], and Banks [1970] that the plasma may

stream out from the polar ionosphere to the magnetospheric tail, depending on the plasma pressure. They have studied a steady state model of the sunlit polar cap for the case of low tail plasma pressure which gives rise to the streaming of thermal polar ionosphere from above the F_2 peak altitude out into the tail. This is consistent with the observations mentioned above. This process may be very efficient in the topside ionosphere, and satellite measurements are also seen to be consistent.

Satellite measurements have revealed the presence of peaks and troughs in ionization density in the topside ionosphere at high and mid-latitudes [Muldrew, 1965; Sharp, 1966; Nelms and Chapman, 1969]. Reddy et al [1967] found enhancements of electron density at 640 Km in the winter high latitudes during magnetic storms for comparatively low sunspot years [1963]. These could be associated with the storm-time F_2 peak features seen in this study of a high solar activity period. It is worthwhile to investigate these storm-time F_2 features for a period of low solar activity, and to correlate them with the development of the normal F_2 anomaly. These investigations are being carried out.

ACKNOWLEDGMENT

The authors wish to express their gratitude to Professor K. R. Ramanathan for valuable advice during the course of the work. They thank Doctor J. W. King of Radio and Space Research Station, Slough, for his helpful discussion at Delhi on the effects of thermospheric winds on the ionosphere.

Manuscrit reçu le 26 mai 1971.

Appleton E. V., Naismith R. and Ingram L. J., "British Radio Observations during second International Polar year 1932-1933," *Phil. Trans. Royal Soc.*, **A236**, 191-259, 1937.

Appleton E. V. and Piggott W. R., "Storm Phenomena and solar cycle variations of the $F2$ layer ionisation at noon," *Physics of the Ionos.* Physical Soc., London, 219-228, 1955.

Berkner L. V. and Seaton S. L., "Systematic Ionospheric changes associated with geomagnetic activity," *Terr. Mag. and Atmos. Elec.*, **45**, 419-423, 1940.

Banks P. M., "Plasma Transport in the topside polar ionosphere," The polar ionosphere and magnetospheric processes, Gordon and Breach, New York (in press), 1970.

Banks P. M. and Holzer T. E., "The polar wind," *J. Geophys. Res.*, **73**, 6841-6854, 1968.

Bergh H. W., "The time-lag between magnetic and ionospheric changes," *J. Atmos. and Terres. Phys.*, **24**, 949-958, 1962.

Croom S. A., Robbins A. R. and Thomas J. O., "Variation of electron density in the ionosphere with magnetic dip," *Nature*, **185**, 902-903, 1960.

Dougherty J. P., "On the influence of horizontal motion of the neutral air on the diffusion equation of the F-region," *J. Atm. and Terr. Phys.*, **21**, 167-176, 1961.

Duncan R. A., "Universal time control of the Arctic and Antarctic F-region," *J. Geophys. Res.*, **67**, 1823-1830, 1962.

Groves G. V., "Correlation of upper atmospheric air density with geomagnetic activity, November 1960," *Space Research*, II, 751-753, 1961.

Jacchia L. G., "Satellite drag during the events of November 1960," *Space Research*, II, 747-751, 1961.

Jacchia L. G., "The temperature above the thermopause," *Space Research*, V, 1152-1174, 1965.

Kavanagh L. D., Freeman J. W. and Chen A. J., "Plasma Flow in the magnetosphere," *J. Geophys. Res.*, **73**, 5511-5519, 1968.

Kohl H. and King J. W., "Atmospheric winds between 100 and 700 km and their effects on the ionosphere," *J. Atm. and Terr. Phys.*, **29**, 1045-1062, 1967.

Krankowsky D., Kasprazak W. T. and Nier A. O., "Mass Spectrometric studies of the composition of the lower thermosphere during summer 1967," *J. Geophys. Res.*, **73**, 7291-7306, 1968.

Martyn D. F., "Geomorphology of $F2$ region ionospheric storms," *Nature* (London), **171**, 14-16, 1953 *c*.

Martyn D. F., "The normal F-region of the ionosphere," *Proc. IRE.*, **47**, 147-155, 1959.

Matsushita S., "A study of the morphology of ionospheric storms," *J. Geophys. Res.*, **64**, 305-321, 1959.

Mafda K. I. and Sato T., "The F-region during magnetic storms," *Proc. of the IRE*, **47**, 232-239, 1959.

Muldrew D. B., "F-layer ionisation troughs deduced from Alouette data," *J. Geophys. Res.*, **70**, 2635-2650, 1965.

Mathews B. N., "Universal control of low-energy electron fluxes in the polar regions," *J. Geophys. Res.*, **73**, 3459-3468, 1968.

Nelms G. L. and Chapman J. H., "The high-latitude ionosphere — results from the Alouette ISIS topside sounders," Proc. of NATO Advanced Study Institute, Norway, 1969.

Nisbet J. S. and Quinn T. P., "The recombination coefficient of the night-time F-layer," *J. Geophys. Res.*, **68**, 1031-1038, 1963.

Piddington J. H., "A theory of Aurorae and the ring current," *J. Atmos. and Terr. Phys.*, **29**, 87-105, 1967.

Polyakov V. M., "Determination of the electron recombination rate in the $F2$-layer from the diurnal ionisation variation," *Geomagnetizm in Aeronomiya*, **5**, 702-709, 1963.

Rastogi R. G. and Rajaram G., "Abnormal behaviour of $f2$ 0 at Huancayo in magnetically active periods of IGY-IGC," *J. of Atmos. and Terres. Phys.*, **27**, 1097-1103, 1965.

Reddy B. M., Brace L. H. and Findlay J. A., "The ionosphere at 640 km on quiet and disturbed day," *J. of Geophys. Res.*, **72**, 2709-2727, 1967.

Rishbeth H. and Setty C. S. G. K., "The F-layer at sunrise," *J. Atm. and Terr. Phys.*, **20**, 263-276, 1961.

Ratcliffe J. A., "The formation of ionospheric layers $F1$ and $f2$," *J. Atmos. Terres. Phys.*, **8**, 260-269, 1956.

Rishbeth H., "A review of ionospheric F-region theory," *Proc. IRE.*, **55**, 16-35, 1967 *a*.

Rishbeth H., "On explaining the behaviour of the ionospheric F-region," *Rev. of Geophys.*, **6** (1), 33-71, 1968.

Sharp G. W., "Mid-latitude trough in the night ionosphere," *J. Geophys. Res.*, **71**, 1345-1356, 1966.

Strobel D. F. and McElroy M. B., "The $F2$-layer at middle latitudes," *Planet. Space Sci.*, **18**, 1181-1202, 1970.

Seaton M. J., "A possible explanation of the drop in F-region critical densities accompanying major ionospheric storms," *J. Atmos. Terres. Phys.*, **19**, 122-124, 1956.

Schmeltekopf A. L., Fehsenfeld F. C., Gilman G. I. and Ferguson E. E., "Reaction of atomic oxygen ions with vibrationally excited nitrogen molecules," *Planet. Space Sci.*, **15**, 401-406, 1967.

Thomas J. O., "Electron density distribution in the $F2$ layer of the ionosphere in winter," 'Electron density distributions in the ionosphere and exosphere' p. 226, edited by Thrane, 1964.

Thomas L., "$F2$-region disturbances associated with major magnetic storms," *Planet. Space Sci.*, **18**, 917-928, 1970.

13

WALDTEUFEL P., "A study of seasonal changes in the lower thermosphere and their implications," *Planet. Space Sci.*, **18**, 741-748, 1970.

WULF O. R., "Winter-summer differences in geomagnetic activity," *J. Geophys. Res.*, **76**, 1837-1840, 1971.

FIG. 1

Variation of $D_m(f_0F_2)$ (mean ratio $f_0F_2/\overline{f_0F_2}$ during the first 48 hours of storms) with dip angle north and south.

FIG. 2

Variation of $D.Q(f_0F_2)$ and all-day average f_0F_2 with dip angle north and south for midday and midnight hours.

FIG. 3

Variation of u/U and w/U with dip angle for Quiet and Disturbed conditions.

IGY - IGC

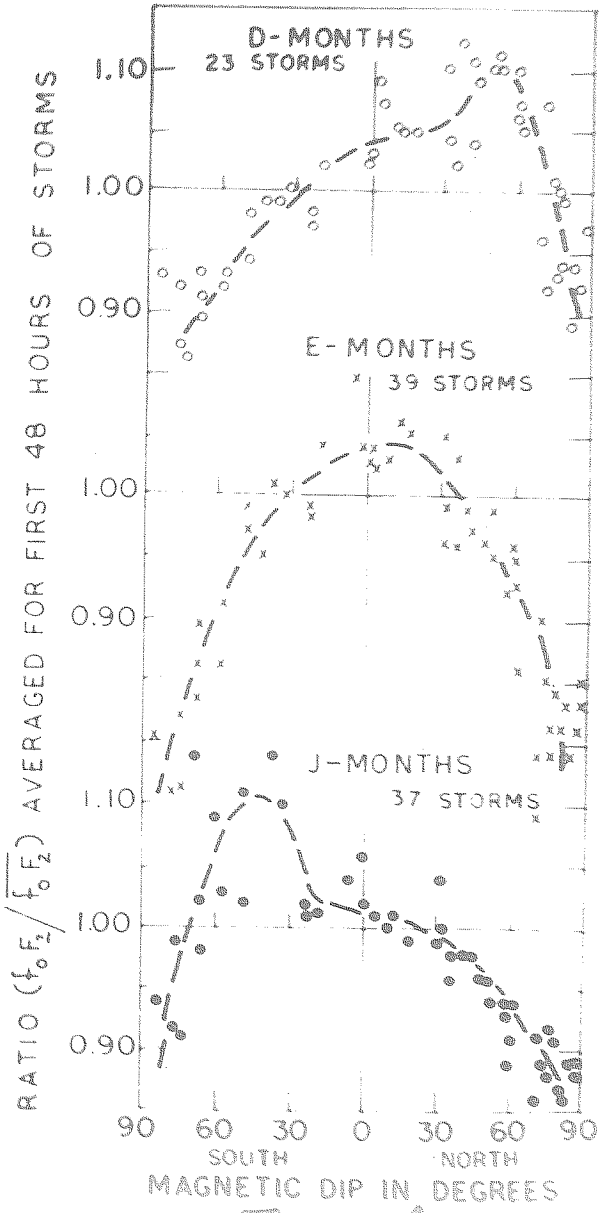


FIG. 1

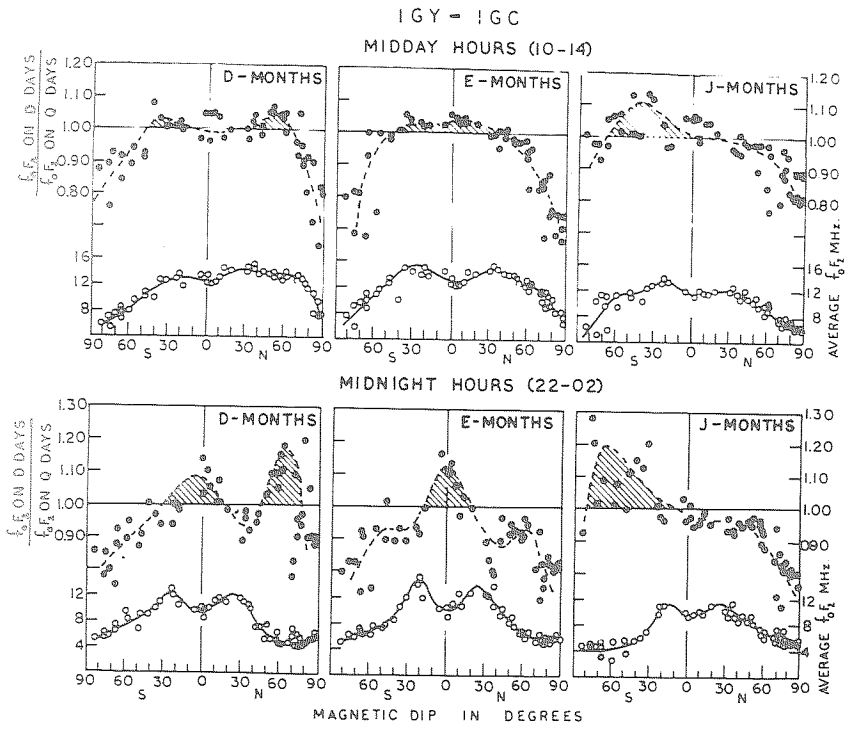

IGY - IGC
MIDDAY HOURS (10-14)
D-MONTHS
E-MONTHS
J-MONTHS
MIDNIGHT HOURS (22-02)
AVERAGE f_0F_1 MHz.
MAGNETIC DIP IN DEGREES

FIG. 2

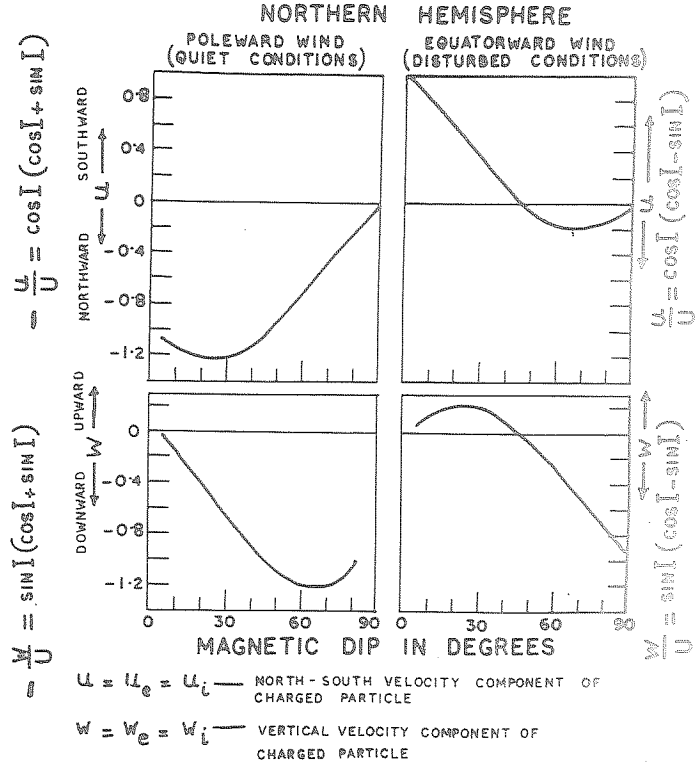

NORTHERN HEMISPHERE
POLEWARD WIND (QUIET CONDITIONS)
EQUATORWARD WIND (DISTURBED CONDITIONS)
SOUTHWARD
NORTHWARD
UPWARD
DOWNWARD
MAGNETIC DIP IN DEGREES
$u = u_e = u_i$ — NORTH-SOUTH VELOCITY COMPONENT OF CHARGED PARTICLE
$w = w_e = w_i$ — VERTICAL VELOCITY COMPONENT OF CHARGED PARTICLE

FIG. 3

(1) Changes in solar radiation, both electromagnetic and corpuscular.

(2) Changes in atmospheric temperature which can cause the chemical reaction and attachment rates to alter considerably.

(3) increased turbulence which can affect the atmospheric composition and thus the reaction kinetics.

Changes in transport div (Nv) can arise from -

(1) Electromagnetic drifts of ionisation arising from electric fields set up during disturbed conditions.

(2) horizontal transport of ionisation by neutral winds arising from thermal and pressure gradients set up by non-uniform atmospheric heating.

At the highest latitudes - the most important process would be the polar wind which blows away ionisation into the tail region of the magnetosphere (Banks and Holzer 1968; Banks 1970). The intensity of the wind is greater during disturbed conditions owing to increased solar wind velocities, and more ionisation would be blown into the tail at such times. This partly account for decreased

f_oF_2 at these latitudes at all times. A greater decrease in summer is understandable because of magnetospheric asymmetry, the summer polar cap being more directly exposed to the sun, and experiencing greater solar wind velocities. The effect of precipitating particles in the polar regions through ionisation, heating, and inflow of hot plasma into the F-region has been dealt with by Marubashi (1970).

The auroral latitudes - too generally experience a decrease of f_oF_2 . These latitudes are the most directly accessible to solar corpuscular radiation and are sinks of a large amount of thermal energy arising from frictional heating, Joule heating, and magnetic mirror heating. It is the heating effect which is most important here. It increases the recombination rate of the reaction (Schmeltekopf et al., 1967, Matuura 1963; Yonezawa 1963).

$$O^+ + N_2 \longrightarrow NO^+ + N$$
$$NO^+ + e \longrightarrow N^* + O^*$$

and could cause considerable loss of ionisation. The heating also sets up neutral winds which blow equatorwards (J.W.King 1970; Cole 1962; Hook 1970) and carry away some ionisation to lower latitudes. Direct observations of thermospheric winds with velocities of 250 to 400 m/sec. blowing from the auroral regions towards the equator during two geomagnetic

storms have been made with Fabry-Perot interferometers by Hays and Roble (1971). Experimental evidence of such equatorward winds during storm conditions have also been obtained by backscatter radar studies at Saint Santin-Nancay (Alcadé et al., 1971), barium-cloud experiments in Sweden (Stoffregen 1971), and Doppler shift measurements of 6300 A^{o} night airglow (Nagy et al., 1971).

Electrodynamic drift effects arising from interaction between the DS currents and the geomagnetic field here could partly contribute to the horizontal transport of ionisation to lower latitudes.

At mid-latitudes - Neutral thermospheric winds play an important role here. A general idea of neutral wind effects on the F-region has been presented in Ch. 2. In summer the overall wind directions are towards the winter hemisphere and carry away the lighter O atoms with them, leaving behind the heavier N_2 and O_2 molecules. The winter hemisphere is thus richer in atomic oxygen, which is ionised more easily. Typical values of the O/N_2 ratio are, after Waldteuffel (1970).

		Summer	Winter
At 350km	O/N_2	6.9	12.2

Changes in the ratios O/O_2 and O/N_2 at the turbopause have been shown to considerably alter electron density profiles in the F-region (Chandra and Herman 1969; Obayashi and Matuura 1971).

The recombination coefficient β is less in the winter hemisphere than in the summer hemisphere (Polyakov 1963; Nisbet and Quinn 1961; Bergh 1962; Bhargava and Subrahmanyan 1964), typical values being

	Summer	Winter
β =	3×10^{-4}/sec.	1.8×10^{-4}/sec.

(after Risbeth and Setty 1961)

The enhanced production rate and the decreased loss rate in the winter hemisphere are features of even quiet-time conditions, and could account for the F-region seasonal anomaly of enhanced f_oF_2 in winter mid and high-latitudes. During disturbed conditions an additional effect of an equatorward wind from the auroral and high latitudes comes in. This opposes the normal thermospheric wind blowing from the summer hemisphere to the winter hemisphere, and the two wind-systems pile up ionisation in the region centred around 55° dip where the hump of enhanced D/Q (f_oF_2) is seen in Fig. 2 of the Paper. Such a hump could be formed in the summer hemisphere at the same dip region, as there would be two opposing wind-systems there too. It is likely that this does not show up because of the larger recombination rates in summer.

In the night-time, both the wind-systems — the normal thermospheric winds as well as the winds associated with auroral heating — act unidirectionally from the poles towards the equator, and blow ionisation up along the magnetic field lines. The ionisation is taken up into regions of smaller loss, and once again a prominent increase is seen in the mid-latitudes.

Jones and Rishbeth (1971) have shown theoretically that in middle latitudes, enhancement of F_2 peak electron density can be caused by equatorward neutral winds. Obayashi (1971) feels that the neutral winds. causing positive storm effects at mid-latitudes, are driven largely by pressure gradients set up across the plasmapause.

Equatorial and low-latitudes - are governed chiefly by a weakening of equatorial electric fields during disturbances, and to some extent by the thermospheric winds described above. Many workers have shown a relationship between the equatorial electrojet and F_2 critical frequencies at the anomaly crest and trough (Dunford 1967, 1970; Mac Douggall 1969; Balsley and Woodman 1969, Ketadia and Patel 1970) (All references in Ch. 6) during quiet conditions. This is supported by Rastogi and Rajaram(1971) from their study of f_oF_2 at equatorial Kodaikanal and sub-tropical Ahmedabad.

In addition, Ch. 6 describes observations which strongly support the suggestion that the equatorial electric fields weaken during disturbed conditions, and after the onset of geomagnetic storms. The electron density distributions over the equator during storms resembles that on a weak electrojet day; in addition the equatorial anomaly trough is filled up on disturbed days. Section 7.3 has dealt with the mechanisms by which this weakening of electric field can occur.

The effect which neutral winds have at different dip regions is shown in Fig. 3 of the Paper. The lower part shows a substantial change in the vertical drift 'W' of a charged particle from quiet to disturbed conditions. At lower latitudes the downward drift during quiet conditions changes into an upward drift during disturbed conditions. This is supported by the increase in $h_{max}\ F_2$ generally observed at equatorial stations during disturbed conditions (Ch. 4 and Ch. 6). This prevents ionisation from descending into the lower atmospheric regions with their higher collision frequencies and higher recombination rates. The loss rate is thus reduced and there is enhanced ionisation in low latitudes during disturbed conditions.

A few simple calculations can be made from Fig.3

Considering the north-south velocity component of charged particles, if the poleward neutral wind has a value U_1 and the equatorward neutral wind has a value U_2, for the northern hemisphere,

For quiet conditions:

$$-u/U_1 = \cos I (\cos I + \sin I)$$

For disturbed conditions

$$u/U_2 = \cos I (\cos I - \sin I)$$

At some region in mid-latitudes where there is a dumping of ionisation, the velocities of the charged particles blown in by the two wind systems has to be equal and opposite

$$\frac{U_2}{U_1} = \frac{\cos I + \sin I}{\sin I - \cos I}$$

In the daytime, the dip region at which peak dumping occurs is 50° and $\frac{U_2}{U_1} \approx 11$

In arriving at this ratio of U_2/U_1, one must remember that this is only an approximation. Dougherty's equations of motion for charged particles themselves contain some approximations, and these have been further simplified.

This ratio is therefore a very rough approximation, and its value should be used only to infer that the wind originating from the poles U_2 during storms has a higher velocity than the one originating from low latitudes U_1.

7.5 Disturbed F_2 behaviour in low sunspot years.

(a) Differences between high and low sunspot

The differences in D/Q (f_oF_2) behaviour between high and low sunspots have been shown in Fig. 5.3, and have been elucidated in Section 5.4. To recapitulate the main features:

(1) There is a low-latitude enhancement of D/Q (f_oF_2) centred about the dip equator in both epochs; an exception to this are the midnight hours of the J-months in high sunspot years.

(2) In both epochs there is a tendency for a relative drop in D/Q (f_oF_2) around 30° dip north and south in all seasons, most markedly in the daytime hours. In the night-time there are deviations from this behaviour.

(3) In both epochs, at winter mid-latitudes there is a hump of enhanced D/Q (f_oF_2). In the low sunspot years this hump is not so well pronounced. The summer hump is absent in the high sunspot but present in low sunspot. In the

equinoxes, high sunspot years show an enhancement of D/Q (f_oF_2) within $\pm 30^o$ dip and a simple decrease beyond; in the low sunspot years, mid-latitude humps of D/Q (f_oF_2) are seen in both hemispheres of the equinoxes.

(4) In high sunspot years the summer hemisphere shows decreased D/Q (f_oF_2) beyond 30° dip. The low sunspot years, however, show a decrease of D/Q (f_oF_2) only beyond 75° dip in the summer hemisphere, this being more prominent in the southern hemisphere than in the northern hemisphere.

The salient differences in the disturbed f_oF_2 behaviour between the two sunspot epochs is, that in low sunspot years, a far wider range of latitudes experience increased f_oF_2 during disturbances in all seasons. It is only at the very high latitudes-the polar cap latitudes — that a decrease of disturbed f_oF_2 occurs; this is more true of the southern high latitudes in the East zone. Clearly these observations are not in accordance with the classical ideas which believe in a decrease of f_oF_2 always at high latitudes, and a seasonal change-over of winter positive to summer negative effects in f_oF_2 at mid-latitudes. While they do hold in high sunspot years, they are certainly not valid in low sunspot years.

(b) Differing atmospheric conditions

The differences in f_oF_2 behaviour between the two sunspot epochs still can be explained, using the same mechanisms for disturbances as discussed for high sunspot years. The outstanding differences in the F_2 behaviour could be due to the differences in atmospheric conditions, and these are

(1) Atmospheric temperatures vary from 600^oK to 1800^oK between periods of low and high solar activity at heights of 300 km and more. This is shown in Fig. 7.1 (Pg. 201(a)) from CIRA 1965 after Nicolet (1961). This means that neutral temperatures change by a factor of almost 3 between sunspot minimum and sunspot maximum, at F_2 peak heights and above.

(2) Magnetic storms have a greater frequency and intensity in high sunspot periods than in low. This is observed from a systematic scanning of A_p values during the 3 days following every storm which occurred at Huancayo from 1938 to 1966, a period covering over two complete solar cycles. A_p values on the whole have a direct proportionality to the solar activity index, and hence larger values are found in high sunspot years. Low sunspot years show small values of A_p .

201(a)

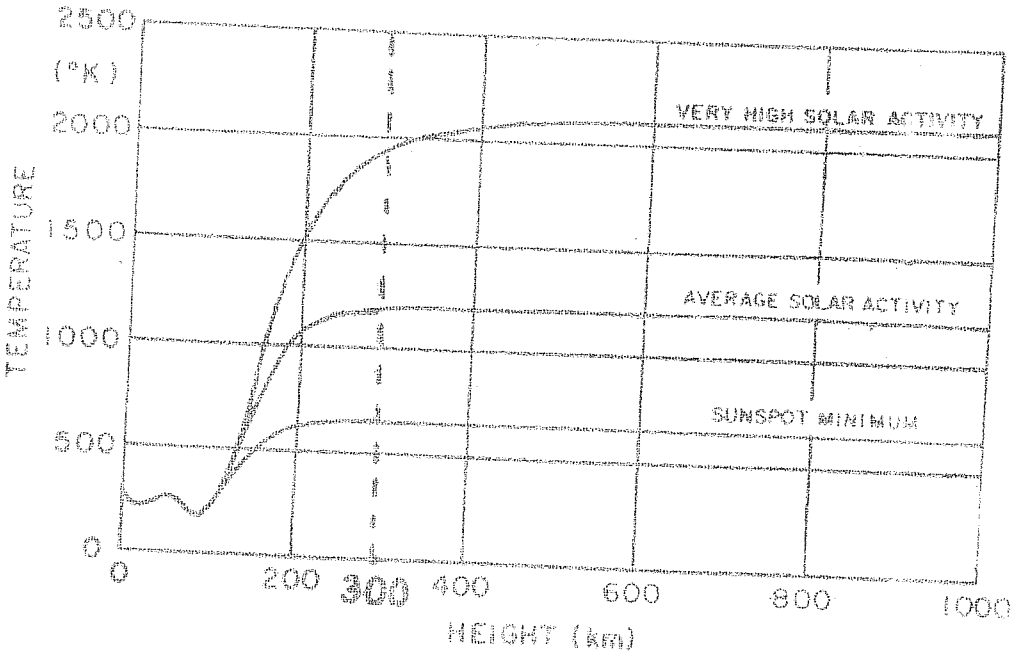


Fig. 7.1 Atmospheric temperature profiles for three stages of solar activity (Nicolet 1960; 1961).

This implies that in high sunspot years, solar corpuscular radiation during storms would be more intense, energetic and frequent, and a larger number of high energy particles would enter at auroral latitudes, setting up greater frictional heating and stronger associated DS current systems. In low sunspot years, the corpuscular radiation is weaker and less frequent, and the auroral regions will consequently experience a smaller flux of particles; this means less frictional heating, and less Joule heating associated with weaker DS current systems. For the same reasons the solar wind blowing polar plasma into the magnetospheric tail would be less intense in low sunspot years than in the high.

(c) One can study how these features fit in with the disturbed f_0F_2 behaviour during low sunspot.

(1) Highest latitudes

At polar latitudes the decrease in disturbed f_0F_2 is far more in the high sunspot years than in the low. This is understandable on the basis of the stronger storm-time polar wind during high sunspot which would blow away a greater amount of ionisation into the magnetospheric tail. This would be less in low sunspot years, hence the smaller decrease in disturbed f_0F_2

At auroral latitudes a smaller number of energetic particles would enter in low sunspot years. This means less frictional heating and smaller Joule heating, as the currents would be less intense. The change in temperature caused by storms is less and atmospheric temperatures themselves are less. The recombination rate is consequently less than in high sunspot years, and no marked decrease of disturbed f_oF_2 is seen in low sunspot years at these latitudes. In fact what is actually observed here is an increase of disturbed f_oF_2. The reason for this may be the limited particle precipitation, which without its accompanying thermal effects, can actually contribute to the increase in observed ionisation. The thermospheric winds set up by thermal gradients too would be expected to be less in the low sunspot years, and there comparatively less horizontal transport of ionisation to the mid-latitudes.

(2) Mid-latitudes - The thermospheric winds originating from auroral and high latitudes due to storm-time heating would be less intense in low sunspot periods. At mid-latitudes there are still two opposite wind systems during disturbed conditions bringing in some ionisation from the two sides and forming a hump of ionisation in this region. Humps are seen in the mid-latitudes of both hemispheres in

low sunspot years because the recombination coefficients may not be vastly different between the summer and winter hemispheres. Also smaller summer to winter thermospheric temperature gradients in low sunspot years could cause less upwelling of atomic oxygen from the summer to winter hemisphere. These two causes could be responsible for the seasonal anomaly in f_oF_2 not being observed in the low sunspot years. This can be seen from Fig. 2.4 (Pg.45 (a)) in which the only anomaly which can be observed in low sunspot years is the December anomaly with overall December f_oF_2 greater than June f_oF_2 . For the same reasons, the hump in disturbed f_oF_2 shows up in the mid-latitudes of both hemispheres in all seasons, though the winter hump remains slightly sharper. At mid-latitudes, the $h_{max}\ F_2$ level does not differ greatly from high solar activity to low solar activity as it does at the equator. The recombination rates for the mid-latitude F_2 region are thus more a function of temperature, not of altitude.

(3) <u>At equatorial and low-latitudes</u> - the same features of enhanced f_oF_2 during disturbances in low latitudes centred about the equator, and the relative decrease in D/Q (f_oF_2) around $\pm$ 30° dip (the region of anomaly crests) are seen in both sunspots. This is understandable as these latitudes are less subject to the different heating and particle precipitation effects associated with

the different sunspot epochs. and the storm effects are comparatively independent of these. In the low as in the high, the storm f_oF_2 effects in the latitude belt $\pm 30^o$ dip would be explained by:

(1) A weakening of equatorial electric fields causing reduced $\vec{E} \times \vec{B}$ vertical drift, and reduced transport of ionisation from the equator to the anomaly crests.

(2) Neutral wind systems which reduce the downward velocity component of charged particles during disturbed conditions thereby preventing them from going into regions of greater loss and recombination, and resulting in enhanced f_oF_2.

Both these features cause increase in f_oF_2 under disturbed conditions at these latitudes.

7.6 Electron density distribution studies.

The studies of electron density distributions at true heights at equatorial stations discussed in Ch. 4 have not yielded pronounced differences between magnetically Quiet and Disturbed days. True heights of the F_2 peak $h_{max}F_2$, generally increase when $N_{max}F_2$ increases, and decrease when $N_{max}F_2$ decreases, and this behaviour

is fairly consistent. The semi-thickness y_m however does not change in a consistent way. Both $N_{max}\ F_2$ (the F_2 peak electron density) and N_T (the total electron content from F_2 peak to the ionispheric base) generally increase at equatorial stations during disturbed conditions as compared to quiet. The only exception is in December solstitial months, when occasionally there is a tendency for both to decrease.

7.7 Suggestions for future work.

(1) The D_{st} (f_oF_2) studies carried out here are the average behaviour of a large number of storms. Some workers (Cole; Private communication) feel that it is better to study the D_{st} characteristics for the 3 phases of the storm- the initial, main and recovery phases separately, as they are three widely-differing processes with different physics behind each. This type of study would be laborious to execute for a large number of storms at a large number of stations, but it can be undertaken on a more selective basis.

(2) The true height changes of the F_2 layer during magnetic disturbances should be investigated on a world-wide basis. This would throw more light on the part played by storm-time wind systems and electromagnetic drifts in

causing movements of ionisation. It requires access to ionograms from stations situated at different latitudes, and a cooperative effort in reducing the ionograms to true height profiles. Only equatorial stations in the two longitude belts have been examined here for F_2 height changes, owing to availability of the ionograms concerned.

(3) It is important to combine simultaneous observations from topside probes and ground-based sounders at locations all over the world. It is this alone which can give an authentic and integrated picture of what exactly happens during magnetically disturbed conditions. With an international approach, this should be done for at least a few selected storms.

(4) Exact calculations of the magnetic mirror heights of charged particles with various energy spectra would be useful in determining their contribution to storm-time F_2 ionisation at different latitudes. The feature of the daytime winter spur in quiet f_oF_2, shifting over to 60° dip of the summer hemisphere by night, merits more attention. All these processes which have been suggested as responsible for the observed F_2 storm effects are qualitative, and certainly need quantitative investigation. The calculation of probable thermal and pressure gradients, the wind velocities which would be set up at the appropriate

heights, the magnitudes of electromagnetic drifts set up by storm-time currents - each of these is a problem by itself.

7.8 Epilogue

Mechanisms which explain the observed ionospheric F_2 disturbance effects at all latitudes satisfactorily, have been suggested. These conclusions have been arrived at chiefly on the basis of global f_oF_2 studies during magnetically quiet and disturbed conditions, for both high and low sunspot epochs. A detailed study of the height and electron distribution changes for equatorial stations has been made, but as pointed out, has not yielded a prominent change during disturbed conditions. The phenomenon of magnetic disturbances is admittedly a complex one. While the mechanisms proposed may have their weaknesses, the plea for them is that they have been suggested logically on the basis of an intensive study of important F-region parameters, and existing ideas. More sophisticated methods of probing the ionosphere may test the validity of the mechanisms suggested.

REFERENCES

CHAPTER - I

Akasofu S.I., S.Chapman, and C.I. Meng	1965	J. Atmos. and Terr.Phys., 27, 1275
Alfvén, H.	1950	Cosmical Electrodynamics, Ch. 2.
Axford, W.I., and C.O. Hines	1961	Canad. J. Phys., 39, 1433.
Bailey, D.K.	1959	Proc. I.R.E., 47, 255.
Baker, W.G., and D.F. Martyn	1953	Phil. Trans. Roy.Soc., London, A246, 281
Baker, W.G.	1953	Phil. Trans. Roy.Soc., London, A246, 295
Balsley, B.B.	1966	Ann. Geophys., 22, 460
Bartels, J.	1957	Ann. Intern. Geophys. Year, 4, 209
Biermann, L.	1951	Z.Astrophysik, 29, 274.
Biermann, L.	1952	Z.Naturforsch, 7a, 127
Cahill, L.J., and P.G. Amazeen	1963	J. Geophys.Res., 68, 1835.
Chapman, S.	1951	In "The Earth's Magnetism" Methuen Monographs, London.
Chapman, S.	1963b	In "Geophysics:The Earth's Environment" P.373, Gordon and Breach, New York
Chapman, S.	1919	Phil.Trans.Roy.Soc., A218, 1
Coleman, P.J., C.P. Sonett, D.L.Judje, and E.J.Smith	1960	J.Geophys. Res., 65, 1865
Coon, J.H.	1966	P.231, In "Radiation trapped in the earth's magnetic field" ed. by B.M. Mc. Cormac.

Davis, T.N., K.Burrows, and J.D. Stolarik	1967	J.Geophys.Res.,64, 1665.
Dessler, A.J.	1961	In "Satellite environment Handbook"ed. by F.S.Johnson.
Dungey, J.W.	1958	"Cosmic Electrodynamics"
Dungey, J.W.	1961	Phys.Rev. Letters, 6, 47.
Dungey, J.W.	1963	In "Geophysics:the earth's environment" p.505, Gordon and Breach, New York.
Egedal, J.	1947	Terr. Mag. Atmos.Elec. 52, 449.
Egedal, J.	1948	Nature, 161, 443.
Elsasser, W.M.	1950	Rev. Mod. Phys, 22, 1
Fan, C.Y., P.Meyer, and J.A. Simpson.	1960	Space Res.Vol. 1, 951.
Fan, C.Y., P.Meyer, and J.A. Simpson	1960	Phys.Rev.Letters, 5, 269
Fejer, J.A.	1953	J.Atmos. and Terr. Phys., 4, 184.
Freden, S.C., and R.S. White	1959	Phys. Rev. Letters, 3, 9
Gold, T.	1959	J. Geophys.Res., 64, 1665.
Gringauz, K.I.	1961	Space Res., 2, 539.
Kamiyama, H.	1966	Rep. Ionosphere Space Res., (Japan) 20, 171.
Kato, S.	1956	J. Geomagn. and Geoelec. (Japan) 8, 24.
Maeda, H.	1955	J. Geomagn. and Geoelec. (Japan), 7, 121.
Mc. Nish, A.G.	1937	I.A.T.M.E. Bull, 10, 271.

Mc.Ilwain, C.E.	1961	J. Geophys. Res., 66, 3681.
Maynard, N.C. and L.J. Cahill Jr.	1965a	J. Geophys. Res., 70, 5923.
Maynard, N.C. and L.J. Cahill Jr.	1965b	J. Geophys. Res., 70, 5975.
Ness, N.F. and J.M. Wilcox	1966	Astrophys. J., 143, 23.
Neugebauer, M. and C.W. Snyder	1966	J. Geophys. Res. 71, 4469.
Nishida, A., N.Iwasaki, T. Nagata	1965	Ann. Geophys. 22, 478.
Northrup, T.G., and E.Teller	1960	Phys. Rev. 117, 215.
Obayashi, T., and J.A. Jacobs	1957	J.Geophys. Res., 62, 589.
Obayashi, T.	1967	Ch. 5 in "Solar-Terrestrial Physics" ed. by J.W.King and W.S. Newman.
Obayashi, T. and A.Nishida	1968	Space Sci. Rev. 8, 3.
O'Brien, B.J.	1967	Ch. 6 in "Solar Terrestrial Physics" ed. by J.W.King and W.S. Newman.
Parker, E.N.	1958	Phys. Fluids, 1, 171.
Parker, E.N.	1958	Astrophys. J., 128, 664.
Parker, E.N.	1962	Space Sci. Rev., 1, 62.
Piddington, J.H.	1960	J.Geophys.Res., 65, 93.
Piddington, J.H.	1964	Space Sci. Rev., 3, 724.
Rastogi, R.G.	1959b	J.Geophys.Res., 64, 727.
Rastogi, R.G.	1962a	J.Atmos. and Terr. Phys., 24, 1031.

Rees, M.H. 1963 Planet. and Space Sci., 11, 1209.

Reid, G.C. 1967 In "Physics of Geomagnetic Phenomena" - Vol.11-2, ed. by S.Matsushita and W.H. Campbell.

Sastry, T.S.G. 1968 J.Geophys. Res., 73, 1789.

Schuster, A. 1908 Phil. Trans. Roy. Soc., A208, 163.

Singer, S.F., E.Maple, and W.A.Bowen Jr. 1952 Nature, 170, 1093.

Stewart Balfour 1883 Encyclopaedia Brittanica, 16, 159.

Stormer C. 1955 In "The Polar Aurora".

Van Allen, J.A. 1959 Phys. Rev. Letters, 3, 9.

Vestine, E.H., L.Laport, I.Lange, and W.E.Scott. 1947 In "The geomagnetic field - its description and analysis" Carnegie Instt. Pub. No. 580.

Wolfe J.H., R.W. Silva, D.D. Mc. Hibbin and R.H. Mason 1966 c J.Geophys. Res., 71, 3329

CHAPTER - 2

Appleton, E.V. 1935 Phys. Rev., 47, 704.

Appleton, E.V. 1946 Nature, 157, 691.

Appleton, E.V. 1947 J.Inst. of Elec. Engr., 94, 186.

Appleton, E.V. 1950 J.Atmos. and Terres. Phys., 1, 106.

Bailey, D.K. 1948 Terres. Mag. and Atmos.Elec., 53, 41.

Bannon, J. and F.Wood.	1946	Terres. Mag. and Atmos.Elec., 51, 89
Becker, W.	1966	In "Electron density Profiles" ed. by J.Frihagen, p. 218
Berkner, L.V., H.W.Wells, and S.L. Seaton	1936	Terres. Mag. and Atmos.Elec., 41, 173.
Bhargava, B.N. and R.V. Subrahmanyan	1962	Proc. Ind.Acad. of Sci., 55, 330.
Budden, K.G.	1954	Rep. Camb.Conf.on Ionos. Phys. Phys.Soc. London, P.332.
Calvert, W.	1962	N.B.S. Technical Note
Chapman, S.	1956	Nuovo Cimento, 4, 1385
Croom, S.A., A.R. Robbins and J.O. Thomas	1960	Nature, 185, 1960.
Dougherty, J.P.	1961	J.Atmos. and Terr.Phys., 20, 167.
Eyfrig, R.	1963	Ann. Geophys.(France), 19, 102.
Ganesh, K.S.	1965	J.Atmos. and Terres. Phys., 27, 645.
Geisler, J.E.	1966	J. Atmos. and Terres. Phys., 28, 703.
Geisler, J.E.	1967b	J.Atmos. and Terres. Phys., 29, 1469.
Hanson, W.B. and F.S. Johnson	1960	Memoires, Soc. Roy. Soc.Liege.
Heisler, L.H.	1958	Austral J. Phys. 2, 79.
Hines, C.O.	1965	Planet and Space Sci., 13, 169.
Hinteregger, H.E., K.R. Damon, L.Heroux, and L.A. Hall.	1960	Space Res. 1, 615.
Istomin, V.G.	1960	Artificial Earth Satellites.

Jacchia, L.G.	1965	Space Res. V, North-Holland, Amsterdam, 1135.
Jacchia, L.G.	1963	Rev. Mod. Phys., 35, 973.
Johnson, F.S.	1964	Internal Rep. S.W. Centre for Advanced Studies, Dallas, Texas, U.S.A.
Johnson, C.Y., E.B.Meadows, and J.C. Holmes	1958	J. Geophys. Res., 63, 443.
Kasuya, I.	1957	J. Radio Res. Labs.(Japan) 4, 291.
King, G.A.M.	1964	J. Atmosph. Sci., 21, 231.
King, J.W. and H.Kohl	1965	Nature, 206, 699.
King-Hele, D.G.	1964	Planet. and Space Sci., 12, 835.
Kohl, H., and J.W. King	1967	J. Atmos. and Terr. Phys., 29, 1045.
Kotadia, K.M.	1963	J.Atmos. and Terr. Phys., 25, 179.
Liang, P.H.	1947	Nature (GB), 160, 642.
Lyon, A.J., and L.Thomas	1963	J. Atmos. and Terr. Phys., 25, 373.
Maeda, K., H.Uyeda, and H.Shinkawa	1942	Rep. Phys. Inst. Rad.Waves, 2 ,
Martyn, D.F.	1959	Proc. I.R.E., 47, 147.
Martyn, D.F.	1959	J. Geophys. Res., 64, 2178.
Matuura, N.	1963	J. Radio Res. Labs.(Japan), 10, 1.
Minnis, C.M.	1952	J. Atmos. and Terres. Phys., 2, 261.

Munro, G.H. 1958 Austral. J. Phys., 11, 91.

Norton, R.B., T.E.Van Zandt and J.S.Denison 1962 Proc. Int.Conf. Ionosp., London, p. 26.

Paulson, J.F. 1964 Ann. Geophys.(France), 20, 74.

Poloskov, S.M. 1960 Space Res. 1, North Holland Pub. Co. Amsterdam, p. 95.

Ranzi, I. 1939 Ricerca Sci. 10, 926.

Rastogi, R.G. 1958 Geofis. Pura Applicato-Milano (Italy) 40, 145.

Rastogi, R.G. 1959a Canad. J. Phys., 37, 874.

Rastogi, R.G. 1959b J. Geophys. Res. 64, 727.

Rastogi, R.G. 1966 J. Instit. Tele. Engr.(India), 12, 245.

Rastogi, R.G. 1970 Nature (GB), 225, 258.

Rao, C.S.R., and P.L. Malhothra 1964 J. Atmos. and Terres. Phys., 26, 1075.

Ratcliffe, J.A., 1956a J. Atmos. and Terres. Phys., 8, 260.

Rishbeth, H. 1962 In "Electron density profiles" ed. B. Machlum, p. 284.

Rishbeth, H. and C.S.G.K. Setty 1961 J. Atmos. and Terres. Phys., 20, 263.

Ross, W.J. and L.J. Blumle — 1962 Proc. Int. Conf. on Ionosp. London, p. 84.

Rush, C.M., S.V. Rush, L.R. Lyons, and S.V. Venkateswaran — 1969 Rep. of Deptt. of Meteorology, Univ. at California of Los Angeles (USA).

Sanatani, S. — 1966 "Electron density distribution in the Ionosp" - Ph.D.Thesis of Gujarat University.

Sato, T., and G.F. Rourke — 1964 J. Geophys. Res., 69, 4591

Schmeltekopf, A.L., F.C.Fehsenfeld, G.I. Gilman and E.E., Ferguson — 1967 Planet. and Space Sci., 15, 401.

Shimazaki, T. — 1959 Radio Res. Labs.(Japan) 6, 669.

Taylor, G.N. — 1966 In "Electron density profiles" ed. J.Frihagen, p. 543.

Thomas, J.O. — 1959 Proc. I.R.E., 47, 162.

Thomas, J.O. — 1962 In "Electron density profiles" ed. B. Machlum, p. 134.

Thomas, J.O. — 1963a J. Geophys. Res., 68, 2707.

Thomas, L., and R.B. Norton — 1966 J. Geophys. Res., 71, 227.

Thomas, L. — 1968 J.Atmos. and Terres.Phys., 30, 1631.

Wright, J.W. 1962 Nature (GB), 194, 461.

Yeh, K.C., and B.J. Flaherty 1966 J. Geophys. Res., 71, 4557.

Yonezawa, T. 1959 J. Radio Res. Lab. (Japan), 6, 651.

Yonezawa, T., and Y. Arima 1959 J. Radio Res. Lab.(Japan), 6, 293.

Yonezawa, T., and H.Takahashi 1960 J. Radio Res. Lab.(Japan), 7, 335.

Yonezawa, T. 1963 Proc. Inter. Conf. Ionosph. London, p. 128.

Yuen, P.C., and T.H. Roelofs 1967 J. Atmos. and Terres. Phys., 29, 321.

CHAPTER - 3

Appleton, E.V., and L.J. Ingram 1935 Nature (G.B.), 136, 548.

Appleton, E.V., and W.R. Piggott 1952 J. Atmos. and Terres. Phys., 2, 236.

Becker, W. 1964 "Electron density distributions" ed. E.Thrane, North-Holland, Amsterdam, p. 152.

Berkner, L.V., H.W.Wells and S.L. Seaton 1939 J.Geophys. Res., 44, 283.

Berkner, L.V., and S.L. Seaton — 1940 — Terres. Mag. and Atmos. Elec., 45, 419

Bhargava, B.N., and R.V.Subrahmanyan — 1962 — J. Atmos. and Terres. Phys., 24, 321.

Brace, L.H., B.M. Reddy, and H.G. Mayr — 1967 — J.Geophys. Res., 12, 265.

Brown, G.M., and R.Wynne — 1967 — Planet. and Space Sci., 15, 1677.

Budden, K.G. — 1954 — Rep. Camb. Conf. on Ionos. Phys. (Phys. Soc. London), p. 332.

Cahill, L.J. — 1966 — J. Geophys. Res., 71, 4505.

Carpenter, D.L. — 1963 — J. Geophys. Res., 68, 1675.

Carpenter, D.L. — 1966 — J. Geophys. Res., 71, 693.

Carlson, H.c. and W.E. Gordon — 1966 — In "Electron Density Profiles" ed. by J.Frihagen North Holland, Amsterdam.

Coleman, P.J., L.Davis, E.J. Smith and C.P. Sonnett. — 1962 — Science, 138, 1099.

Chandra, S. and R.A. Goldberg — 1964 — J. Geophys. Res., 69, 3187.

Chandra, S., B.E.Troy Jr., J.L. Donley, and R.E. Bourdeau — 1970 — J.Geophys. Res., 75, 3867.

Chapman, S. — 1936 — In "The Earth's Magnetism" Methuen, London.

Dalgarno, A. 1964a Ann. Geophys.(France), 20, 65.

Dieminger, W., and K.H. Geisweid 1950 J. Atmos. and Terres.Phys., 1, 42.

Evans, J.W. 1965 J. Geophys.Res., 70,2726.

Gledhill, J.A., D.G. Torr and M.R. Torr 1967 J. Geophys. Res., 72, 209

Gordon, W.E. 1966 Presented at 15th General Assembly of URSI, Munich (Sept. 1966).

Groves, G.V. 1961 Rep. Univ.College, London.

Hanson, W.B., and R.J. Moffett 1966 J. Geophys. Res., 71, 5559.

Hibberd, F.H., and W.J. Ross 1967 J. Geophys. Res., 72, 5331.

Jacchia, L.G. 1964 Planet and Space Sci, 12, 355.

Jacchia, L.G. 1961 Space Res., 2, 747.

King, G.A.M. 1962a Planet. and Space Sci., 2, 95.

King, G.A.M. 1967 J. Atmos. and Terres. Phys., 29, 161.

King, J.W. 1961 J. Atmos. and Terres. Phys., 21, 26.

King, J.W., K.C. Reed, E.O. Olatunji, and A.J. Legg 1967 J. Atmos. and Terres. Phys., 29, 1355.

Klobuchar, J.A., H.E. Whitney, and R.S.Allen	1964	In "Electron density distributions ....."ed. by E.Thrane, North Holland Amsterdam, p. 250.
Knecht, R.W., and R.E.Mc. Duffie	1962	J. Phys.Soc.Japan, 17, 280.
Kotadia, K.M.	1966	J. Atmos. and Terr. Phys., 28, 143.
Kotadia, K.M.	1967	Ann. Geophys.(France), 23, 1
Maier, E.J.R.	1968	J. Geophys.Res., 74, 185.
Martyn, D.F.	1953	Nature (GB), 171, 14.
Martyn, D.F.	1953	Proc. Roy. Soc., A218, 1.
Matsushita, S.	1959	J. Geophys. Res., 64, 305.
Matsushita, S.	1963	Proc. Int. Conf. on Ionos. (Phys. Soc. London), p.120
Meek, J.H.	1952	J. Geophys.Res., 57, 177.
Millman, G.H.	1964	In "Electron density distributions....."ed. E.Thrane, North Holland, Amsterdam, p. 256.
Newton, G.P., R. Horowitz, and W. Priester	1965	Planet. and Space Sci., 13, 599.
Nishida, A.	1967	J. Geophys. Res., 72, 6051.
Obayashi, T.	1954	Rep. Ionos.Res.in Japan, 8. 165.

Obayashi, T. 1952 Rep. Ionos.Res. in Japan, 6, 79.

Obayashi, T. 1959 J. Radio. Res. Labs.(Japan), 6, 375.

Obayashi, T. 1962 Nature (GB), 196, 24.

Oksman, J., and E.Kataja 1962 Ann. Acad. Sci.Fennicae, Helsinki, Ser A. 6 Physica, No. 115.

Ondoh, I. 1967 J. Radio Res. Labs. (Japan), 14, 267.

Rao, P.B. 1968 J. Geophys. Res., 73, 1661.

Rastogi, R.G. 1962 J. Geophys. Res., 67, 1367.

Ratcliffe, J.A. 1951 J. Geophys. Res., 56, 463.

Reddy, B.M., L.H. Brace, and J.A. Findlay 1967 J.Geophys. Res., 72, 2709

Sato, T. 1957b J. Geomagn, and Geoelec (Japan), 9, 57.

Schilling, G.F., and C.A.Whitney 1959 Planet and Space Sci, 1, 136.

Schmerling, E.R. 1958 J. Atmos. and Terr. Phys., 12, 8.

Shapley, A.H., and R.W. Knecht. 1957 Trans. I.R.E., 5, 326.

Skinner, N.J., and R.W.Wright 1955 J. Atmos. and Terr. Phys. 6, 177.

Somayajulu, Y.V. 1963 J. Geophys. Res., 68, 189.

Thomas, J.O., and M.D.Vickers. 1958 DSIR Radio Res. Space Rep. No. 28.

Thomas, J.O., and A.Robbins 1958 J. Atmos. and Terr. Phys., 13, 131.

Thomas, L., and F.H. Venables 1966 J. Atmos. and Terr. Phys., 28, 599.

Titheridge, J.E., and M.K. Andrews 1967 Planet. and Space Sci, 15, 1157.

Warren, E.S. 1959 Proc. I.E.E.E.(USA),57, 1029.

Watt T.M. 1966 J.Geophys.Res., 71, 3131.

Willmore, A.P. 1965 Proc.Roy.Soc.London, A286, 537.

CHAPTER - 4

Appleton, E.V., and W.R. Piggott 1952 J. Atmos. and Terres. Phys., 2, 236.

Antarctic Research Series 4 1965 A.G.U. Pub.Ed. by A.H. Waynick.

Banks, P.M., and T.E. Holzer 1968 J.Geophys.Res., 73, 6841.

Bhargava, B.N., and U.V. Gopala Rao 1959 Indian J. Meteorol.Geophys., 10, 203.

Chandra Harish 1969 "Studies of low-latitude ionisation" -Ph.D. Thesis of Gujarat University.

Cladis J.B., and A.J. Dessler	1961	J. Geophys. Res., 66, 343.
Dungey, J.W.	1961	Phys. Rev. Letters, 6, 47.
Evans, J.V.	1965b	J. Geophys. Res., 70, 1175.
Gledhill, J.A., and H.O. Van Rooyen	1962	Nature, 196, 973.
Handbook of Geophysics	1961	U.S. Air Force Res. Div. Pub. by Macmillan.
Harang, L.	1937	J. Geophys. Res., 42, 55.
Heikkila, W.J.	1971	J. Geophys. Res., 76, 1076.
Hilton, H.H., J.R.Stevens, and A.L. Vampola	1964	Tran. Am. Geophys. Union, 45, 602.
Huang, Y.N. and Yeh, C.Y.	1970	J. Atmos. and Terres. Phys., 32, 1765.
Huang Y.N.	1964	J.Geophys. Res., 69, 3633.
Imhof W.L., and R.V. Smith	1965	J. Geophys. Res., 69, 1239.
King, J.W., H. Kohl and R.Pratt	1967	J. Atmos. and Terres. Phys., 29, 1529.
Knudsen, W.C., and G.W.Sharp	1969	"South Pacific electron concentration enhancement from inner radiation belt particles" Presented at XI COSPAR meeting, Tokyo,

Kotadia, K.M., and K.R. Ramanathan	1961	Proc. of IGY Symp. Vol. 1, p. 176 (held at New Delhi).
Mariani, F.	1964	J. Geophys. Res., 69, 556.
Matsushita, S.	1968	Radio Sci., 3, 658.
Narasinga Rao, B.C.	1966	Rep. No. 30 of R.P.U. National Physical Laboratory, New Delhi.
Paulikas G.A., and S.C.Freden	1964	J.Geophys. Res., 69, 1239.
Rajaram, G and R.G. Rastogi	1968	J. Atmos. and Terr. Phys., 30, 651.
Rajaram G. and R.G. Rastogi	1968	Ann. Geophys.(France), 24, 1045.
Rajaram, G., and R.G. Rastogi	1969	Ann. Geophys.(France), 25, 795.
Rajaram,G., and R.G. Rastogi	1970	J. Atmos. and Terres. Phys., 32, 113.
Rajaram, G., and R.G. Rastogi	1970	Ind. J. Pure and Appl. Phys., 8, 551.
Rajaram, G., and R.G. Rastogi	1971	Ann. Geophys.(France), 27.
Rastogi, R.G. and G.Rajaram	1965	J. Atmos. and Terr. Phys. 27, 1097.
Rastogi, R.G.	1960	J. Geophys. Res., 65, 585.
Rastogi, R.G. and S. Sanatani	1963	J. Atmos. and Terr. Phys. 25, 739.

Sharp, G.W., W.L. Imhof and R.G.Johnson 1966 Space Res., 6, 203.

Thomas, L., and F.H. Venables 1966 Planet. and Space Science 15, 1157.

Venugopal, V.R. 1959 Bulletin No. CLI of Kodaikanal Observatory.

Williams, D.J. and J.W. Kohl 1965 J. Geophys. Res., 70, 4139.

CHAPTER - 5

Chan, K.L., and L.Colin 1969 Proc. of I.E.E.E., 57, 990.

King, J.W., K.C. Reed E.O. Olatunji and A.J. Legg 1967 J. Atmos. and Terres. Phys., 29, 1355.

Lockwood, G.E.K., and G.L. Nelms. 1964 J.Atmos. and Terres. Phys., 26, 569.

Nagata, T., and T.Oguti 1953 Rep. Ionos. Res. in Japan, 7, 21.

Narasinga Rao, B.C. 1966 Rep. No. 30 of R.P.U. National Physical Laboratory, New Delhi.

Obayashi, T. 1954 Rep. Ionos. Res. in Japan, 8

Rastogi, R.G. 1960 J.Geophys. Res., 65, 585.

Rastogi, R.G., and G.Rajaram, 1970 Presented at the Symposium on Solar-Terrestrial Physics (Leningrad, May 1970).

Sinno, K. 1954 Rep. Ionos. Res. in Japan, 8,

Symposium ofIonospheric Storms, Japan (1953) 1954 Rep. Ionos. Res. in Japan, 8,

CHAPTER - 6

Abur-Robb, M.F.K. 1969 Planet. and Space Sci., 17, 1269.

Appleton, E.V. 1946 Nature (GB), 157, 1946.

Balsley, B.B., and R.F. Woodman 1969 J. Atmos. and Terres. Phys., 31, 865.

Baxter, R.G., and P.C.Kendall 1968 Proc. Roy.Soc., A304, 171.

Bramley, E.N., and M.Peart 1965 J. Atmos. and Terres. Phys., 27, 1201.

Bramley, E.N., and M.Young 1968 J. Atmos. and Terr. Phys., 30, 99.

Bhargava, B.N., and R.V. Subrahmanyan 1962 Proc. Ind. Acad. of Sci., 55, 330.

Duncan, R.A. 1960 J. Atmos and Terres. Phys., 22, 89.

Dunford, E. 1967 J. Atmos. and Terres.Phys., 29, 1489.

Dunford, E. 1970 J. Atmos. and Terres. Phys., 32, 421.

King, J.W., and H.Kohl	1965	Nature (GB), 206, 1965.
Kotadia, K.M., and J.C.Patel	1970	J. Atmos. and Terres. Phys., 32, 1773.
Martyn, D.F.	1949	Proc. Roy.Soc., A194, 429.
Mc. Douggall Jr.	1969	Proc. of 3rd. Intern. Symp. on equatorial Aeronomy (Held at Ahmedabad), 2, 269.
Misra, R.K.	1971	"Studies of ionospheric irregularities at low latitudes" Ph.D. Thesis submitted to Gujarat University.
Mitra, S.K.	1946	Nature (GB), 158, 668.
Moffett, R.J., and W.B. Hanson	1965	Nature (GB), 206, 705.
Nair, K.N., Rastogi, R.G., and V.Sarabhai	1970	Nature (GB) 226, 740.
Norton, R.B., and T.E.Van Zandt	1964	J.Atmos. and Terres. Phys., 26, 1047.
Obayashi, T.	1971	Rep. of Inst. of Space and Aeron. Sci. University of Tokyo.
Rastogi, R.G.	1959	J.Geophys.Res., 64, 727.
Rastogi, R.G., and S. Sanatani	1968	Ann. Geophys.(France), 28, 75.
Rastogi, R.G., and G.Rajaram	1971	Ind. J.Pure and Appl. Phys., 9, 531.

Rastogi, R.G. H.Chandra and R.K. Misra 1971 Nature (GB), 233, 13.

CHAPTER - 7

Aggson, T.L. 1969 In "Atmospheric Emissions" ed. B.M. Mc. Cormac, Van Nostrand.

Alcade D., P.Bauer, J.Testud, and P. Waldteuffel. 1971 Space Res. 12.

Axford, W.I., and C.O. Hines 1961 Canad . J. Phys., 39, 1433.

Banks, P.M., and T.E. Holzer 1968 J. Geophys. Res., 73, 6841.

Banks, P.M. 1970 In "The polar ionosphere and magnetospheric Processes" Gordon and Breach, N.Y.

Bergh, H.W. 1962 J. Atmos. and Terres. Phys., 24, 949.

Bhargava, B.N. and R.V. Subrahmanyan 1964 Indian J. Meteorol. Geophys., 15, 67.

Bostrom, R. 1967 In "Aurora and Airglow" ed. B.M. Mc.Cormac, Van Nostrand.

Chamberlain, J.W. 1961 Astrophys. J., 134, 401.

Chamberlain, J.W. 1962 Astrophys. J., 136, 678.

Chapman, S. 1937 Terres. Mag.Atmos. Elec., 42, 355.

Chandra, S., and J.R. Herman	1969	Planet. and Space Sci., 17, 841.
CIRA	1965	COSPAR International Reference Atmosphere -North-Holland, Amsterdam.
Cole, K.D.	1962a	Austr. J. Phys., 15, 223.
Cole, K.D.	1963a	J. Geophys. Res., 68, 3231.
Cole, K.D.	1965	Ann.Geophys.(France),21, 156.
Cole, K.D.	1966	Space Sci. Rev., 5, 699.
Cole, K.D.	1971b	Planet. and Space Sci., 19, 59.
Cole, K.D.	1971	Presented at Symp. on Ionosphere -Magnetosphere Interactions, New Delhi, Feb. 1971.
Duncan, R.A.	1969	J. Atmos. and Terres. Phys., 31, 59.
Dungey, J.W.	1961	Phys. Rev. Letters., 6, 47.
Fairfield, D.H., and L.J. Cahill Jr.	1966	J. Geophys. Res. 71, 155.
Fejer, J.A.	1961	Canad. J. Phys., 39, 1409.
Findlay, J., and K.D. Cole	1970	Trans. Am. Geophys. Union (U.S.A.). 51, 378.

Hays, P.B., and R.G. Roble	1971	J. Geophys. Res., 76, 5316.
Hirono, M.	1955	Rep. Ionos. Res. Japan, 9,95.
Hook, J.L.	1970	Planet. and Space Sci., 18, 1623.
Jacchia, L.G. and J.Slowey	1967	Space Res., 7, 1077.
Jones, K.L., and H. Rishbeth	1971	J.Atmos. and Terres. Phys. 33, 391.
Kato, S.	1962	Planet. and Space Sci., 9, 939.
Kern, J.W.	1961	J. Geophys. Res., 66, 1290.
Kern, J.W.	1962	J. Geophys. Res., 67, 2649.
King, G.A.M.	1966	J. Atmos. and Terres, Phys., 28, 957.
King, J.W.	1970	Meeting of Roy. Astron, Soc., London, November, 1970.
Krassovsky, V.I.	1959	Planet. and Space Sci. (GB), 1, 14.
Maeda, K.	1955	Rep. Ionos. Res. Japan, 9,71.
Maeda, K., and T.Sato.	1959	Proc. I.R.E., 47, 232.
Marubashi, K.	1970	J.Radio .Res. Labs. (Japan), 17, 335.

Martyn, D.F.	1953	Proc. Roy. Soc. A218, 1
Matuura, N.	1963	J. Rad. Res. Lab. (Japan), 10, 1.
Moe, K.	1963	Nature (GB), 201, 481.
Nagata, T.	1954	Rep. Ionos. Res. (Japan) 8, 39.
Nagy, A.F., P.B. Hays, and K.D.McWatters	1971	Space Res., 11
Nicolet, M.	1961	Planet. and Space Sci., 5, 1
Nisbet, J.S., and T.P. Quinn	1961	J. Geophys. Res., 68, 1031.
Obayashi, T.	1964	In "Research in Geophysics" ed. Hugh Odishaw, M.I.T. Press. p. 359.
Obayashi, T., and N.Matuura	1971	Proc. of S.T.P. Symposium-Leningrad, May, 1970 (to be published).
Obayashi, T.	1971	Rep. of Instit. of Sp. and Aeron. Sce., Tokyo - (August).
Polyakov, V.M.	1963	Geomagnetism and Aeronomy (U.S.S.R.), 5, 702.
Piddington, J.H.	1964	Space Sci. Rev., 3, 724.

Rajaram, G., A.C. Das and R.G.Rastogi	1971	Ann. Geophys.(Franco) - to be published.
Reddy, B.M., L.H., Brace, and J.A. Findlay	1967	J.Geophys. Res., 72, 2709.
Rishbeth, H.	1963.	Planet. and Space Sci., 11, 31.
Rishbeth, H.	1968	Rev. of Geophys., 6, 33.
Rishbeth, H., and C.S.G.K. Setty	1961	J. Atmos. Terres. Phys., 20, 263.
Rothwell, P.	1963.	Proc. Int. Conf. on Ionos., London, p. 217.
Rostoker, G., and C.J. Fälthammar	1967	J. Geophys. Res. 72, 5853.
Sato, T.	1957	J.Geomag, and Geoelec. (Japan), 9, 1.
Schmeltekopf, A.L. F.C. Fehsenfield, G.I. Gilman, and E.E.Ferguson.	1967	Planet.and Space Sci.,15,401.
Seaton, M.J.	1956	J.Atmos.and Terres. Phys., 8, 122.
Stoffregen, W.	1971	"Magnetosphere-Ionosphere Interactions" -ed. K.Folkestadt Oslo (to be published)
Sonnerup, B.V.O.	1965	J.Geophys.Res., 70, 1051.
Thomas, L.	1970	Planet.and Space Sci.,18,917.
Waldteuffel, P.	1970	Planet. and Space Sci.,18,741.
Yonezawa,T.	1963	Proc.Int.Conf.of Ionos., London, p. 218.