Effect of Electron-Ion Collisions in the F Region of the Ionosphere on the Absorption of Cosmic Radio Noise at 25 Mc/s at Ahmedabad

Changes in Absorption Associated with Magnetic Storms

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Abstract. Measurements of cosmic radio noise at 25 Mc/s, being made at the Physical Research Laboratory, Ahmedabad, since March 1957, have shown much larger values of absorption than those observed by Shain and Mitra in Australia. This fact, together with the empirically known dependence of the absorption on the critical frequency of the F region, and the effect of magnetic storms on the absorption found from the Ahmedabad observations have led us to examine the different possible parameters that may affect cosmic-noise absorption. It is found that electron-ion collisions in the F region both below and above the level of maximum electron density contribute in a substantial way to the absorption of cosmic radio noise. The values of hourly absorption due to collisions of electrons with neutral particles and with ions have been calculated for a period of 6 days in August–September 1957, when there were three magnetic storms. The results obtained show a depletion of electrons *above* F maximum on the day following the commencement of the magnetic storm and a refilling on later days. The results are discussed in relation to findings from satellite observations about particle fluxes in the Van Allen belts during magnetic storms.

Introduction. The cosmic-radio-noise method of measuring ionospheric absorption was used by *Mitra and Shain* [1953] in Australia at 18.3 Mc/s and by *Bhonsle and Ramanathan* [1958] at Ahmedabad at 25 Mc/s. Mitra and Shain showed that the total ionospheric attenuation could be divided into two parts, one of which they attributed to absorption in the *D region* of the ionosphere and the other mainly to absorption in the F region. Applying Mitra and Shain's method of analysis to the Ahmedabad observations, it was noticed that, although the operating frequency of 25 Mc/s was higher than that used in Australia, the magnitude of the total attenuation observed at Ahmedabad during the period 1957 to 1959 was much higher than that observed in Australia (in 1950). This high value of attenuation at Ahmedabad was partly expected, since Ahmedabad is situated near the latitude of the peak of F_2 ionization. Examination of the mean diurnal and seasonal variations of total attenuation at Ahmedabad showed the following features:

1. The monthly mean diurnal curves of the total attenuation exhibited either one or two humps,
2. The first hump occurred in most of the months between 14 and 16 hours local time,
3. Whenever the second hump occurred, it did so in the early part of the night. It was most frequent in equinoxes and some winters.

On examining the Ahmedabad data, it was believed that it would be better to divide the total attenuation into a daytime component 'symmetrical' about noon, and a residual 'nonsymmetrical' component without any implied commitment regarding the region of the ionosphere in which the absorption might originate. Unambiguous correlation of the nonsymmetrical component with the critical frequency f_oF_2 of the F_2 layer showed that its major part originated in the F region, although there might be residual effects originating well above the level of maximum electron density.

Bhonsle [1960] extended the analysis to cover the Ahmedabad data for the whole period of the IGY and IGC, and confirmed the trends of diurnal and seasonal variations of the total attenuation described above. The monthly mean values of the total attenuation exhibited maxima in equinoxes and minima in summer and winter. This feature was repeated from year to year. The seasonal variations of the monthly mean values of f_oF_2 were also similar, and analysis showed a close relationship between them. Figure 1 gives a mass plot of the mean

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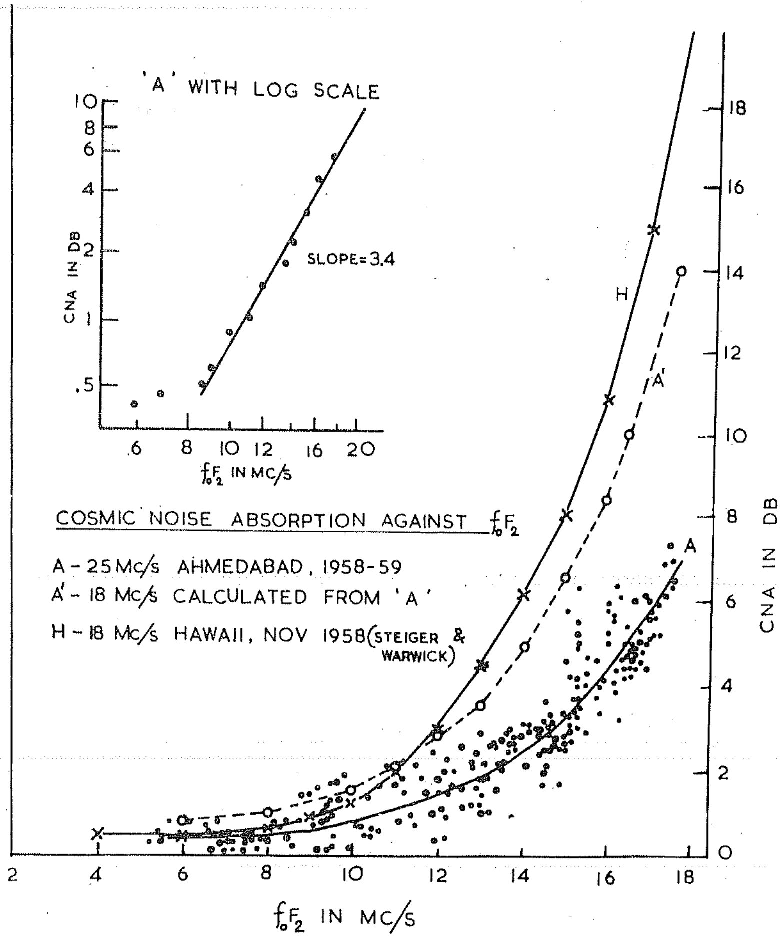

Fig. 1. Cosmic-noise absorption against f_oF_2 at Ahmedabad and Hawaii.

hourly values of cosmic-noise absorption at 25 Mc/s at Ahmedabad in each month of 1958 and 1959. The mean curve is also drawn with logarithmic scales on the left-hand top corner of Figure 1. It is interesting to note that there is an approximately linear relationship between log f_oF_2 and the logarithm of attenuation, when f_oF_2 is greater than 8 Mc/s. Under this condition, the attenuation can be expressed in the form

$$\text{Attenuation}^1 = K + \lambda(f_0F_2 - 8)^{3.4}$$

[1] The significance of λ and of the exponent 3.4 is discussed in the Appendix. The mean curves of attenuation at 18 Mc/s as observed by *Steiger and Warwick* [1961] at Hawaii and as calculated from the Ahmedabad curve for 25 Mc/s assuming an inverse square relationship with f_oF_2 are also drawn in the same figure.

In a study of the effect of magnetic storms on the total attenuation of cosmic noise, *Bhonsle and Ramanathan* [1960] found that the total attenuation became abnormally low on the first 2 days after the sudden commencement of the storm but increased to values above normal on the third day after the commencement. The observed changes in attenuation associated with magnetic storms were tentatively explained as being due to changes in f_oF_2 and in F scatter.

Many years ago, *Cowling* [1945] showed that when an electron moves through an atmosphere containing uncharged atoms and molecules and comparatively fewer ions, the effective cross section for collision between an electron and an ion is much larger than that for a collision between an electron and a neutral particle. In calculating the collision frequencies of electrons in the ionosphere, we have to take into account not only collisions between electrons and neutral particles but also collisions of electrons with positive ions. Whereas in the D and E regions of the ionosphere the former predominates, the situation is reversed in the F region. The electron-ion collisions in the higher regions of the ionosphere become particularly important in latitudes where the maximum electron densities are high.

In this paper, we first calculate the collision frequencies of electrons at different levels in the atmosphere up to the level of maximum electron density at each hour of a period of 6 days from August 31 to September 5, 1957. In making this calculation, the collisions of electrons with neutral atoms or molecules and with positive ions are both considered. The tables of *Yonezawa* [1960] and of *Nicolet* [1959] have been used for the physical properties of the upper atmosphere. Electron densities at different levels over Ahmedabad have been calculated from the ionospheric vertical-sounding records. For levels above $h_{max}F_2$, two extreme models of electron distribution, one as given by *Al'pert, Dobriakova, Chudensenko, and Shaproi* [1958], and the other by *Kazantsev* [1959], have been used (See also *Garriott* [1960]).

Calculation of absorption in different regions. Following *Chapman and Little* [1957], the nondeviative absorption of radio waves of high frequency f Mc/s in the vertical direction can be written in the form

$$D = A/f^2 \cdots, \cdots, \cdots \qquad (1)$$

where D is the absorption in decibels and

$$A = 1.17 \times 10^{-14} \times \int_0^H N_e \nu \, dh \cdots, \cdots, \cdots \qquad (2)$$

Here

N_e = the number of electrons per cc.
ν = the collision frequency of electrons (number of collisions per second).
dh = an element of path length along the vertical.
H = the maximum height to which integration is taken.

In equation 1, the longitudinal component of gyromagnetic frequency f_L is neglected in comparison with f, and ν in comparison with $6\pi \times 10^6$.

For the collision frequency of electrons with neutral atoms and molecules in the atmosphere, *Nicolet* [1959] has given the formula

$$\nu_{em} = 5.4 \times 10^{-10} N_m T^{1/2} \cdots, \cdots, \cdots \qquad (3)$$

where ν_{em} is the frequency of collision of electrons with neutral particles, and N_m is the total number density of neutral particles (N_2,O_2,O, etc.), and T is the temperature of the atmosphere in degrees Kelvin.

Cowling's expression for the frequency of collision of electrons with positive ions as revised by *Nicolet* [1959] is

$$\nu_{ei} = (34 + 4.18 \cdot \log (T^3/N_e)) N_i / T^{3/2} \cdots, \cdots, \cdots \qquad (4)$$

If we assume that in the ionosphere most of the positively charged particles are singly ionized,

$$N_i \approx N_e$$

TABLE 1

Sample table showing the variation N_m, N_e, ν_{em}, ν_{ei}, and $N_e\nu$ with true height at 15 hours on September 7, 1957, at Ahmedabad. Following Chapman, the notation 2.2^6 is used to denote 2.2×10^6.

Height, km	T, °K	N_m	N_e	ν_{em}	ν_{ei}	$N_e\nu$
70	210		4.2^2	1.1^7		4.2^9
80	197		4.2^2	2.2^6		8.3^9
90	197		1.1^4	4.9^5	1.9^2	5.0^9
100	210	1.5^{13}	3.0^4	1.1^5	4.4^2	3.0^9
120	380	9.6^{11}	1.9^5	1.0^4	1.1^3	2.1^9
140	513	2.2^{11}	2.2^5	2.7^3	8.8^2	7.9^8
160	616	7.9^{10}	2.7^5	1.1^3	8.1^2	5.2^8
180	702	3.5^{10}	3.6^5	5.1^2	8.4^2	4.7^8
200	775	1.8^{10}	4.5^5	2.7^2	9.1^2	5.3^8
250	909	4.9^9	7.9^5	8.0^1	1.3^3	1.3^9
300	1038	1.1^9	1.4^6	2.7^1	2.0^3	2.8^9
350	1140	6.5^8	2.9^6	1.2^1	3.7^3	1.1^{10}
400	1220	2.9^8	3.3^6	5.4^0	3.4^3	1.1^{10}
450	1400	1.1^8	3.1^6		2.5^3	7.8^9
500	1580	6.1^7	2.6^6		1.6^3	4.2^9
600	1580	1.9^7	1.8^6		1.1^3	2.0^9
700	1580	6.9^6	1.3^6		8.0^2	1.0^9
800	1580		9.3^5		6.0^2	5.6^8
900	1580		7.0^5		4.6^2	3.2^8

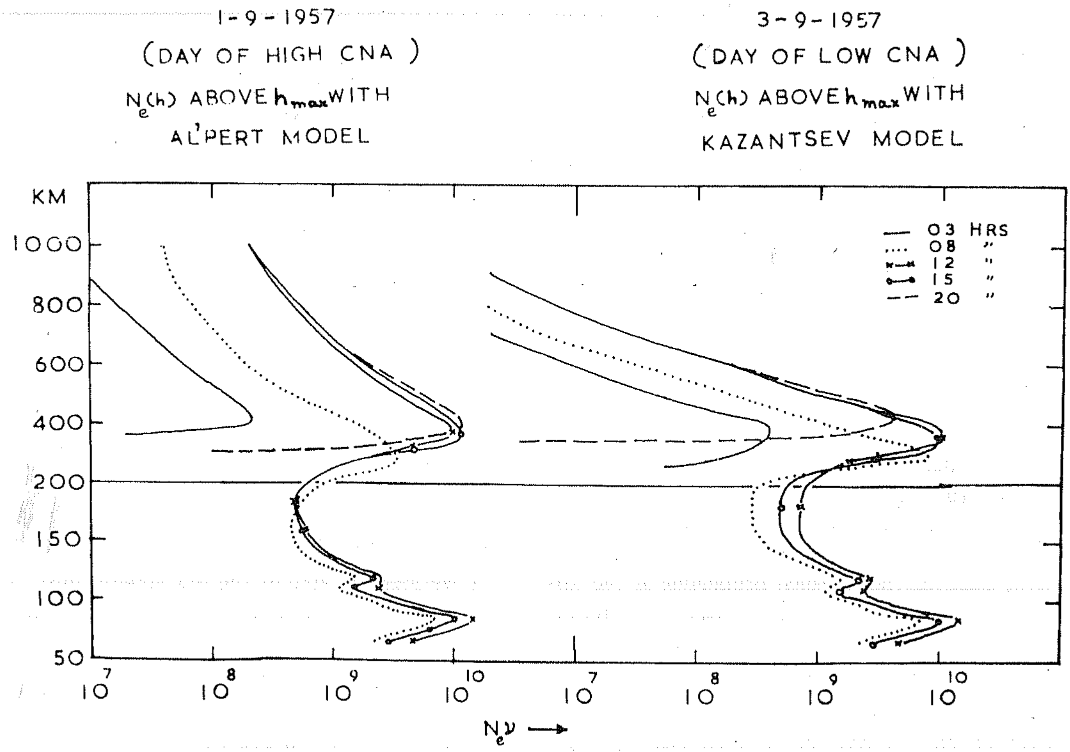

Fig. 2. $N_e\nu$ against height over Ahmedabad at different hours on September 1 and 3, 1957.

For the same electron density, the collision frequency decreases with increase of temperature.

To calculate A in equation 2, ν should be taken to be the sum of ν_{em} and ν_{ei}. The collision cross section of an electron with a positive ion is much larger than that with a neutral atom or molecule. So, while in the D and E regions of the ionosphere, ν_{em} is more important than ν_{ei}, in the F region and above, with decreasing neutral particle density and increasing electron density, ν_{ei} becomes more important. During daytime, ν_{ei} becomes equal to ν_{em} at about 170 km.

The values of N_e for zenith sun at levels below 90 km were taken from *Nicolet and Aikin* [1960] corresponding to disturbed solar conditions. Between 90 and 120 km, they were interpolated from the values at 90 and 120 km. Above 120 km to the level of maximum electron density in F_2 the electron densities were calculated for true heights from the ionospheric sounding records using Schmerling's coefficients. For still higher levels, the values of electron density were estimated on 2 days according to two extreme models, one given by Al'pert and others and the other by Kazantsev. Both these were based on observations of radio waves received from satellites. From these and the number densities of particles at different levels as given by Nicolet (up to 120 km) and by Yonezawa (120 to 420 km), the values of ν_{em} ν_{ei} and $N_e\nu$ were calculated. For levels above 500 km, a uniform temperature of 1580°K was assumed for calculating ν_{ei}. The manner in which ν_{em} and ν_{ei} vary with height is shown in sample Table 1, and the variation of $N_e\nu$ with height in Figure 2. The different curves relate to 3, 8, 12, 15, and 20 hours on September 1 and 3, 1957, over Ahmedabad. The absorptions due to electron-neutral particle collisions and electron-ion collisions were separately calculated. The product $N_e\nu_{em}$ attains a maximum value at about 85 km and falls off with increasing height with a small secondary maximum at 120 km. Above 240 km, only electron-ion collisions are important. The absorption is maximum near the level of maximum ionization of the F region.

Numerical integration of $N_e\nu_{dh}$ was carried out by dividing the ionosphere into 5-km inter-

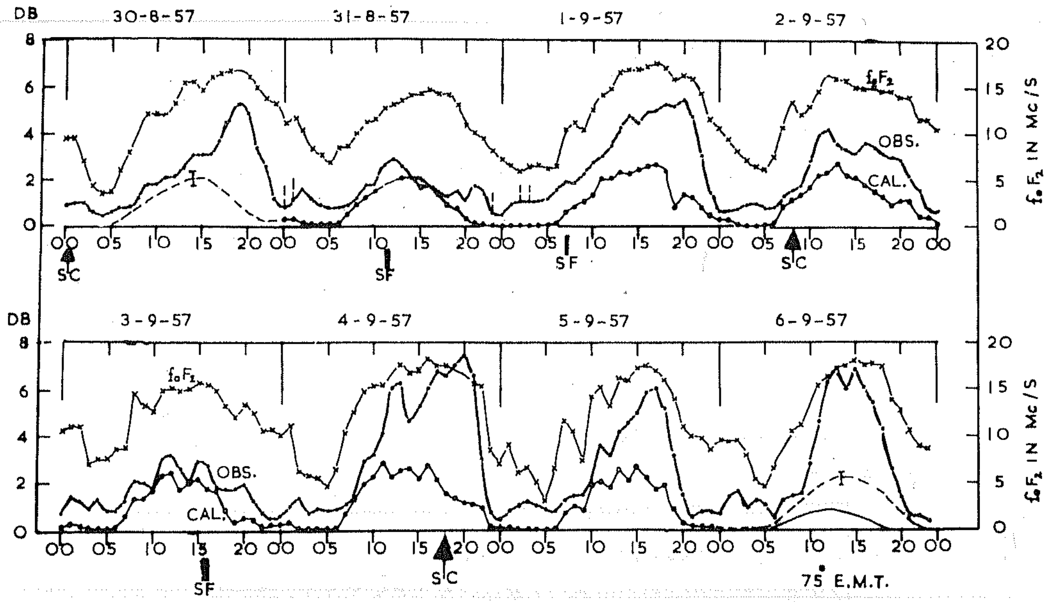

Fig. 3. Observed and calculated values of cosmic-noise absorption at 25 Mc/s and f_oF_2 at Ahmedabad for the period August 30 to September 6, 1957. OBS, observed cosmic-radio-noise absorption at 25 Mc/s at Ahmedabad; CAL, calculated cosmic-radio-noise absorption at 25 Mc/s from N_e (h) profiles at Ahmedabad; f_oF_2, F_2 critical frequency for ordinary waves.

vals between 65 and 120 km, 20-km intervals between 120 km to h_mF_2, and 50-km intervals between h_mF_2 and 1000 km. The calculated absorption in the region 65 to 120 km was about 0.8 db for zenith sun. Absorptions in this region for other values of solar zenith angles were calculated on the assumption that it obeys a $\cos^n \zeta$ law, where $n = 0.75$. Also for this region, the same average electron-density distributions depending on local time were assumed for all the days under investigation.

Comparison of observed values of total attenuation and calculated values of absorption below h_mF. The total ionospheric attenuations measured with cosmic radio noise on 25 Mc/s at Ahmedabad for the period August 30 to September 6, 1957, are plotted in Figure 3. The calculated values of ionospheric absorption below h_mF and the values of f_oF_2 are also plotted in the same figure for comparison. There occurred three SC-type magnetic storms during this period. Their times of commencement are marked in the figure. The measured total attenuations exhibit a diurnal variation with large day-to-day changes. The calculated absorptions for the region below h_mF show a maxima of 2 to 3 db between 13 to 16 hours local time on all these days, and smaller values of absorption in the morning and evening hours. The measured total attenuations are always higher than the corresponding calculated values of absorption for the region below h_mF_2. No doubt this is largely due to the contribution to absorption from regions above F_2 peak.

In Figure 4 are plotted for September 1, 1957, in addition to the measured and calculated absorptions below h_mF_2, the calculated hourly absorptions up to 1000 km, A(A), and A(K), assuming Al'pert's and Kazantsev's models of electron-density distribution above $N_{max}F$. On this day, absorptions calculated on Al'pert's model A(A) were generally in good agreement with observation, though there is some disagreement between the observed and calculated curves in the evening hours. Kazantsev's model gave too small values. On September 3, 1957, a day on which the measured attenuation was abnormally low, the absorptions calculated on Kazantsev's model gave a reasonable fit, but there was some discrepancy in the evening hours. The results can be interpreted to mean that the total number of electrons over

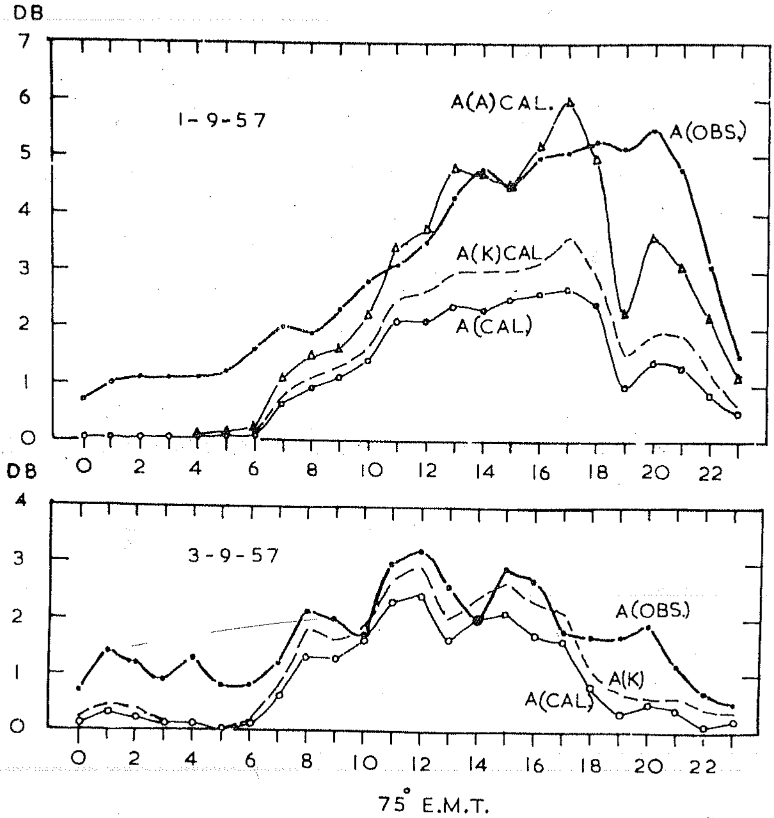

Fig. 4. Observed and calculated absorptions on September 1 and 3, 1957. A(OBS), observed cosmic-noise-absorption on 25 Mc/s at Ahmedabad; A(CAL), calculated cosmic-noise-absorption in the region 65 km to $h_m F_2$; A(K)CAL, calculated cosmic-noise-absorption from 65–1000 km using Kazantsev's model of electron-density distribution above $h_m F$; A(A)CAL, calculated cosmic-noise-absorption from 65–1000 km using Al'pert's model of electron-density distribution above $h_m F$.

unit area above $N_{max}F$ was much less on August 3, 1957, than on September 1, 1957.

The hourly differences between the observed total attenuations and the corresponding calculated values of absorption below $h_m F$ on 8 days from August 30 through September 6, 1957, are plotted in Figure 5. This difference gives us an estimate of absorption occurring in the region above $h_m F$. It appears that (1) large day-to-day changes in absorption occur above $h_m F$ in magnetically disturbed periods; (2) the absorption above $h_m F$ is very much reduced on the second day after the commencement of a magnetic storm; and (3) on the following day the absorption rises up above its prestorm value.

The evidence is strong that the total number of electrons in the atmosphere above $h_m F_2$ is largely depleted in the closing phase of a magnetic storm, and that it is more than restored at the end of the storm.

Discussion. In the above calculations of absorption, only the nondeviative part of absorption due to electron collisions has been taken into account. Deviative absorption and limitation of aerial aperture can also cause attenuation. Both these depend on the nearness of the exploring frequency (25 Mc/s) to the critical frequency of the F_2 layer. Since the maximum critical frequency over Ahmedabad rarely exceeds 18 to 19 Mc/s, and since the angular aperture of the aerial was limited to 40° × 30° in the vertical, it can be shown that the effect of these two can be neglected. It has been pointed out [*Ramanathan and Bhonsle,* 1959]

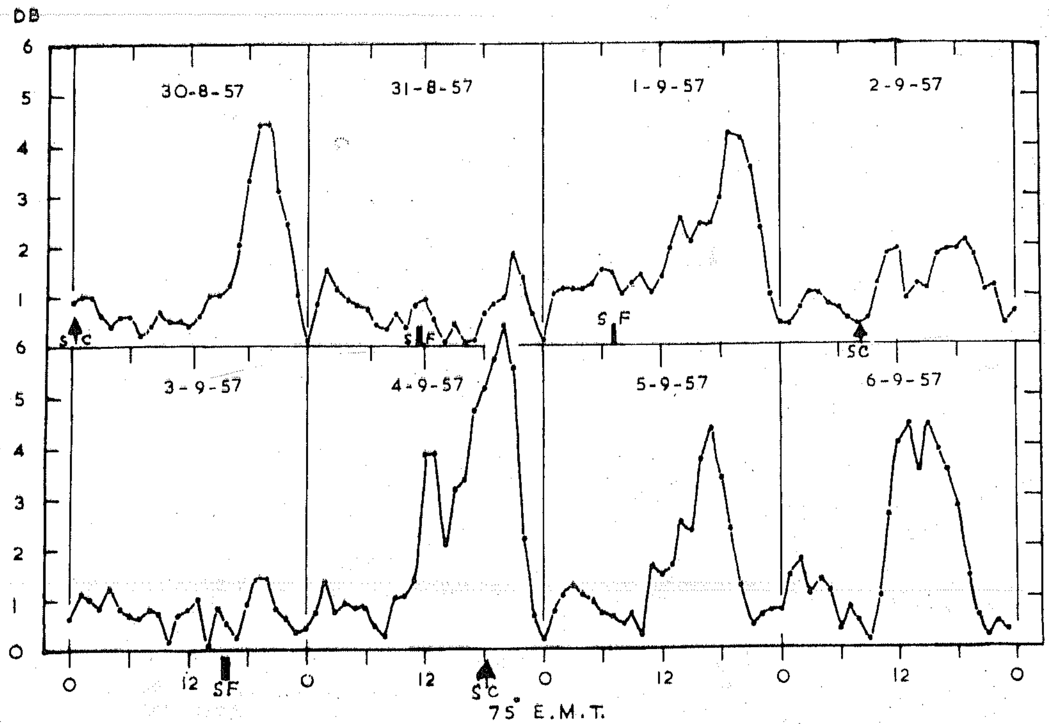

Fig. 5. Difference between observed cosmic-radio-noise absorption on 25 Mc/s and the absorption calculated for the region below h_mF from N_e (h) profiles at Ahmedabad for the period August 30 to September 6, 1957.

that *F* scatter may cause an increase in the attenuation. Examination of day-to-day records shows, however, that *F* scatter can cause either an enhancement or a reduction in the intensity of cosmic noise, depending on the sidereal time and the phase of the daily variation of intensity. This question is under further examination and the results will be reported separately.

Figures 3 and 4 show an additional diurnal increase in absorption in the late evening hours after sunset. This may be due to the following causes: (1) the distribution of electron density with height above F_2 peak may vary with the time of the day. It is probable that at the time when f_oF_2 has begun to decrease in the evening after reaching its peak, there is a delay in the decrease of electron density at levels above the F_2 peak, and (2) there may be a marked diurnal variation of temperature above 300 km in the region where electron-ion collisions contribute toward the attenuation of cosmic radio noise. In fact, there is evidence from rocket and satellite data for both these. *Nisbet* [1960], in a paper on electron-density distribution in the upper ionosphere, has collected together the available rocket and satellite data. They indicate that above f_oF_2 peak high electron densities continue to persist in the late evening hours and that they decrease with height much more rapidly in the second half of the night and in the morning. *Ross* [1960] has shown from the Doppler frequency measurements of satellite 1958δ_2 that on the average, there is a steady increase in total electron content between the F_2 peak and the satellite (height approximately 950 km) from sunrise to sunset, even though the electron content below $h_{max}F$ had begun to show a decrease by sunset. From the data of deceleration of satellites as analyzed by Jacchia, Martin, and Priester, and others, *Nicolet* [1960] concludes that between 300 and 800 km there is probably a cooling during the night of the order of 500°K. Since ν_e is proportional to $T^{-3/2}$, a cooling of the upper part of the ionosphere of this order will cause an increase in the collision frequency of electrons in the ratio of 1.5 to 1.6 if the elec-

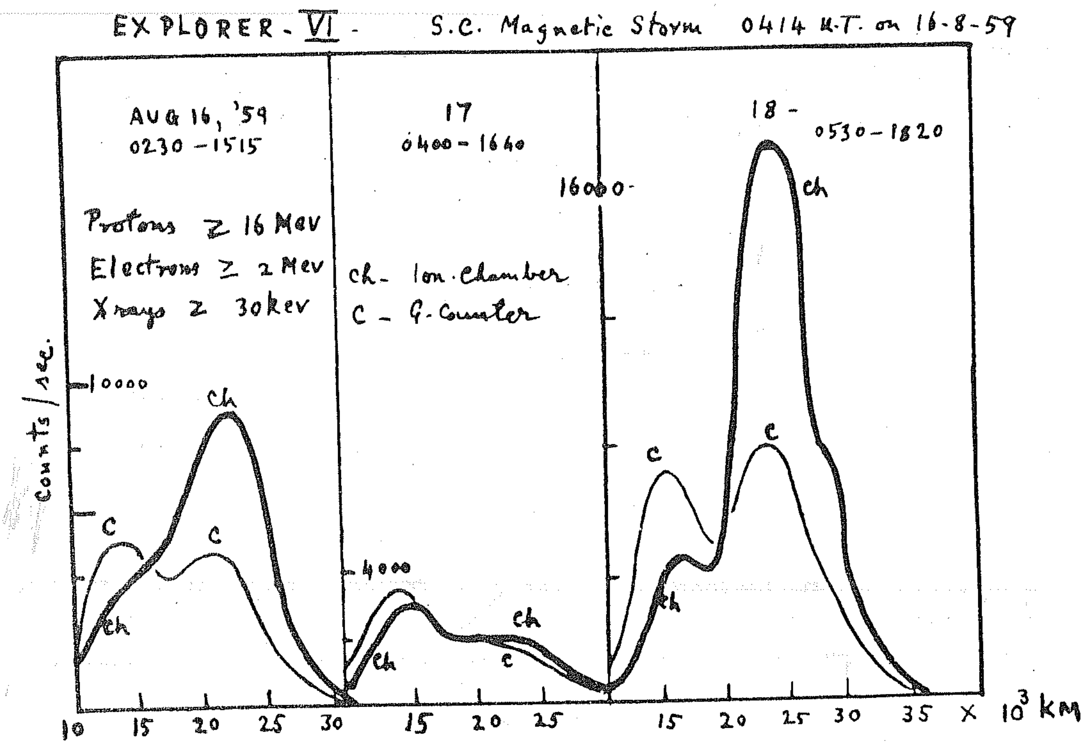

Fig. 6. Particle fluxes in Van Allen radiation belts on August 16, 17, and 18, 1959 (observations with Geiger counter and ion chamber in Explorer VI, after *Arnoldy, Hoffman, and Winckler*).

tron density remains the same. Thus it appears that the post-sunset increase in radio noise absorption is due to the combined effect of a decrease in the temperature of the outer ionosphere, together with a lag in the rate of attachment of electrons with increasing height.

The effect of *F* scatter on the attenuation is quite considerable on some nights and will be dealt with separately.

It is interesting to compare these changes in cosmic noise absorption during and after magnetic storms with the changes in particle fluxes that have recently been observed in Van Allen belts during such storms. Figure 6 shows the observations made by *Arnoldy, Hoffman, and Winckler* [1960] during a magnetic storm that commenced at 0414 UT on August 16, 1959, with instruments carried in Explorer VI. The observations cover a period of 3 days, and the figure shows the counts per second recorded by an ion chamber and a Geiger counter carried in the satellite. The counts of the ion chamber are shown by thick lines and those of the Geiger counter by thin lines. The remarkable feature brought out by the diagram is that on the second day of the storm, there was a large decrease of radiation in the outer Van Allen belt, and this recovered to more than its prestorm value on the third day (August 18). The changes in the harder radiation recorded by the Geiger counter are comparatively smaller, though they are in the same direction. Considering the similarity between the changes in cosmic-radio-noise absorption and the flux of energetic particles in the Van Allen belts, it appears that during magnetic storms there is a large decrease in the number of electrons even in the outer ionosphere in low and middle latitudes during the main phase of a magnetic storm, and that at the end of the storm the outer region gets refilled with electrons. There are now quite a few examples of satellite observations that bear out this general conclusion. Whereas the particle counters carried in satellites measure only energetic particles with energies above certain limits, the cosmic-radio-noise absorption indicates changes in the total number of electrons including slow electrons.

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Appendix

According to equation 2,

$$A = 1.17 \times 10^{-14} \int_0^H N_e \nu \, dh$$

In the F layer, ν_{em} can be neglected in comparison with ν_{ei}, and

$$\nu_{ei} = (34 + 4.18 \log T^3/N_e) N_e / T^{3/2}$$

Now

$$N_e = 1.24 \times 10^4 f^2$$

where f is the plasma frequency in megacycles per second, and

$$N_e \nu_{ei} = (34 + 4.18 \log T^3/N_e) N_e^{\,2}/T^{3/2}$$
$$= 1.54 \times 10^8 (34 + 4.18 \log T^3/N_e) f^4/T^{3/2}$$

In the region between 300 and 1000 km, the factor under brackets can vary from 44 to 50. At the level of maximum electron density $f = f_0F_2$, and since for some distance both above and below that level the plasma frequency may be expected to vary with f_0F_2, and since according to our present understanding of temperatures above the F_2 peak, the temperature increases with height or remains steady at a higher value than at h_mF_2,

$$\int_{300\text{ km}}^{1000\text{ km}} N_e \nu_{ei} \, dh$$

may be expected to vary as some power of f_0F_2 where the exponent is a little smaller than 4.

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