Available online at www.sciencedirect.com
SCIENCE DIRECT®
Advances in Space Research 35 (2005) 866–881
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Sun–Earth relation: Historical development and present status – A brief review

R.P. Kane *

Instituto Nacional de Pesquisas Espaciais, INPE, C.P. 515, CEP 12227-010, São Jose dos Campos, SP São Paulo, Brazil

Received 24 May 2004; received in revised form 12 March 2005; accepted 18 March 2005

Abstract

The Sun and Earth are intimately related. A few decades ago, it was assumed that the relationship was only through the incidence of solar visible and infrared radiation on the surface of the Earth. However, it was soon realized that many powerful solar radiations reached the top of the terrestrial atmosphere but got absorbed in the upper part of the atmosphere, causing significant changes in the terrestrial environment. In this review, various processes are described, first on the Sun where various solar structures evolve, later in the interplanetary space due to escaping solar wind, and further in the interaction of the solar wind with the Earth's magnetic field, containing it in the magnetosphere and entering through the neutral point in the magnetotail. Resulting phenomena like auroras, ring current, etc., are described. Present status of solar and interplanetary environments and their terrestrial effects is briefly outlined.

Keywords: Sun–Earth relations; Solar-terrestrial physics; Interplanetary magnetic field; Solar physics

1. Introduction

Sun–Earth relation has been a fascinating topic ever since humanity inhabited the Earth. The role of solar energy in sustaining agricultural activities and the water resources through cloud cover changes was noted long ago, and human beings are ever grateful to the Sun for its bounty. Since prehistoric times, many cultures have regarded the Sun as a deity. However, until recent decades, the contribution of Sun was assumed to be only in heat and light, which everybody could feel easily. That the Sun might be emitting something more was suspected when people noticed that on hill stations, there were more sunburns. Soon, balloons with instruments were released to sound the upper atmosphere and a plethora of other radiations were noticed in the solar inputs. Most of these, though in percentages smaller than the visible radiation, were highly energetic (ultraviolet (UV), extreme ultraviolet (EUV) and even solar X-rays and gamma rays) and could cause substantial changes in the atmospheric structure. Air molecules were broken up into atoms, and further, atoms were broken up into ions, so that the upper layers of the terrestrial atmosphere (F regions) were almost completely ionized. At lower altitudes, the solar UV intensities decreased and so did the ionization levels so that in the E layer, there were enough neutrals to collide with ions and reduce their mobility. Since electrons were still free to move, electric currents could exist in the E layer and could cause external changes in the geomagnetic field, a bulk of which is otherwise of internal origin with no obvious short-term changes. In what follows, the solar phenomena and their terrestrial effects as they evolved in time, are described (for more details, see reviews Kane, 1976, 1999).

* Tel.: +55 12 3945 6795; fax: +55 12 3945 6810.
E-mail address: kane@dge.inpe.br.

0273-1177/$30 © 2005 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2005.03.142

2. The Sun

The Indian astronomer Aryabhatta (born in 476 A.D.) studied astronomy at the University of Nalanda (Clark, 1930; Kay, 1981; Sen and Shukla, 1985) and made significant contributions to the field of astronomy. He propounded the Heliocentric theory of gravitation, thus predating Copernicus by almost one thousand years. Aryabhatta's Magnum Opus, the *Aryabhatiya* was translated into Latin in the 13th century. Through this translation, European mathematicians got to know methods for calculating the areas of triangles, volumes of spheres as well as square and cube root. The lack of a telescope hindered further advancement of ancient Indian astronomy. Aryabhatta was the first one (in the 5th century A.D.) to propound the theory that the Earth was a sphere. Another Indian astronomer, Brahmagupta, estimated in the 7th century that the circumference of the Earth was 5000 yojanas. A yojana is around 7.2 kms. Calculating on this basis, the estimate of 36,000 kms as the Earth's circumference comes quite close to the actual circumference known today (40,000 kms). Old Sanskrit verses of that epoch say, "there are suns in all directions", and "the night sky is full of suns", indicating that in ancient times, Indian astronomers had arrived at the important discovery that the stars visible at night are similar to the Sun visible during day time. In other words, it was recognized that the Sun is also a star, looking big because of its vicinity to us. This understanding is demonstrated in another verse which says, "when one sun sinks below the horizon, a thousand suns take its place". This apart, many Indian astronomers formulated ideas about gravity and gravitation. Brahmagupta, in the 7th century A.D. had said about gravity, "Bodies fall towards the Earth as it is in the nature of the Earth to attract bodies, just as it is in the nature of water to flow". About a hundred years before Brahmagupta, another astronomer, Varahamihira claimed for the first time perhaps that there should be a force which might be keeping bodies stuck to the Earth, and also keeping heavenly bodies in their determined places. Thus, the concept of the existence of some attractive force that governs the falling of objects to the Earth and their remaining stationary after having once fallen, as also determining the positions which heavenly bodies occupy, was recognized.

In the west, Greek astronomers and philosophers (450–350 B.C.) recognized Sun's sphericity and immensity and explained eclipses. Aristotle (384–322 B.C.) portrayed Sun as a distant sphere but the Earth was considered at the center of the universe. Aristarchus (270s B.C.) was the first one to propose a Heliocentric system, the Earth (not the heavens) rotating daily and circling the Sun, but his ideas were discarded by succeeding astronomers. Within the Earth-centered framework, Apollonius (220s B.C.) proposed eccentric circles and deferent circles with epicycles, while Hipparchus (140s B.C.) used these for modeling the motions of the Sun and the Moon to predict whether solar eclipses would be total, partial, or unobservable at a given location. A few centuries later, Ptolemy (140s A.D.) synthesized earlier work and estimated the distances and sizes of the Sun and the Moon (crudely), all in the Earth-centered framework, and his ideas prevailed in the west with minor variations for several centuries till finally, Copernicus (1473–1543) formulated the concept of Sun-centered planetary system. During the 17th and 18th centuries, natural philosophers and astronomers recognized that the Sun was the nearest star and estimated its distance, size, mass, rate of rotation, and direction of motion through space within ~10% of today's values (Zirin, 1988; Hufbauer, 1991; main sources of the material used in the present brief review). Also, over more than a millennium before the 17th century, observers had noticed sunspots. However, detailed information came only after the invention of the telescope. Some astronomers interpreted sunspots as small planets passing in front of the solar disk. Galileo pleaded that the spots were features of a rotating spherical Sun but was puzzled that they appeared only within 30° of the solar equator. Soon, the Cartesian cosmology was invoked where an infinitude of solar systems existed, scattered through unbounded space. Further details about the Sun were provided, besides many others, by Newton (1642–1727, Sun's mass and density) and Hershel (1738–1822, solar infrared radiation).

In the 19th century, with better instrumentation and eclipse observations, striking features of the Sun ('corona', 'prominences', the colourful region 'chromosphere' between corona and the 'photosphere') were observed, and the study of the Sun's structure and behavior was named as "solar physics". Simultaneously, sustained sunspot monitoring by Schwabe (1843) revealed a ~10-year cycle in sunspot numbers, which Wolf (1876) later corrected to an 11-year cycle. Sabine (1852) revealed that the sunspot maxima and minima coincided in time with maxima and minima of geomagnetic variations, establishing an important Sun–Earth link. Carrington (1858) reported that after a minimum, sunspots appeared on both sides of the solar equator in zones between 20° and 40° latitude, and as the cycle progressed, the spot zones contracted towards the equator, eventually disappearing there at the next minimum. Also, spots near the equator traversed the solar disk more rapidly than those toward either pole (differential rotation, Carrington, 1859a), and on one occasion, short-lived intensely bright and white patches were seen above a sunspot group (first observation of a 'solar flare', Carrington, 1859).

The 19th century and the early part of the 20th century were intervals of the consolidation of solar physics, first by coming out of the earlier domination by pure astronomy, and later by introducing ideas of physics, notably spectroscopy and thermodynamics, developing new instruments, establishing new observatories, and arranging meetings and symposia where solar physicists could compare notes and develop new ideas. By 1910, there were good grounds to consider that the Sun's atmosphere consisted of terrestrial elements heated to the gaseous state (Fraunhofer lines interpreted by Kirchhoff et al., 1859), the photosphere had a temperature of about 6000 K and radiated about 4×10^{24} cal/s, the angular velocity was greater at the solar equator than its poles, there was an 11-year cycle in sunspot numbers, chromospheric activity and coronal shape varied along with the sunspot cycle, and sunspots were the seat of strong magnetic fields. A substantial contribution came from George Hale who developed spectroheliography, started the *Astrophysical Journal,* established the Yerkes Observatory and Mount Wilson Solar Observatory, organized the International Union for Cooperation in Solar Research, installed the first tower telescope, and came up with convincing evidence of high magnetic fields in sunspots (detailed references in Hufbauer, 1991), and a 22-year cycle of solar magnetic field variations. Hale regarded the Sun as key to the study of stars.

In the next three decades (1910–1940), solar physicists from various observatories around the globe were keeping the Sun under constant surveillance, publishing the results in the *Quarterly Bulletin on Solar Activity*, and using the results to examine Sun's influence on radio transmissions and geomagnetism. Also, new means of monitoring the Sun were developed, such as, coronagraphs, solar cinematography, and the monochromatic filter. Equally impressive was the contribution to solar physics of new theoretical tools and results based on recent physical research. The Sun's internal constitution was examined using Eddington's theory of radiative equilibrium, Russel's work on the Sun's composition, and Bethe's identification of thermonuclear reactions. It was concluded that there was an overwhelming abundance of hydrogen in the Sun (and probably all stars). The internal temperature of the Sun was estimated to be about 15 million K, mainly caused by a chain of nuclear reactions (carbon cycle), which began with a proton tunneling into a carbon nucleus and culminated, after the tunneling of three more protons one by one into the nucleus, with the division of the resultant nucleus into a carbon nucleus and a helium nucleus. The energy came from the conversion of mass (m) into kinetic and radiant energy by the Einstein formulation $E = mc^2$. The outward flow of radiation created a pressure that counterbalanced the superincumbent matter's immense weight. Only near and below the surface where the temperature and density were much lower, a 'convection zone' supplemented radiation as an important means by which Sun's heat continued its outward journey. A major puzzle was that there were several coronal emission lines which could be attributed only to emissions from atoms stripped of many of their electrons (e.g., coronal green line 5303 Å arose from fourteen-times ionized iron atoms) and such large scale stripping needed coronal temperatures of about 2 million K. What was the origin of this abnormal coronal heating?

During World War II, observational and interpretive solar physics programs were disrupted, but some scientists were able to convince their governments that solar observations were useful for forecasting ionospheric shortwave transmission characteristics and had military value. Thus, some additional facilities for research could be established which became handy in the decade following the war. British and American scientists had detected solar radio emission (start of solar radio astronomy) and German V-2 rockets could send instruments above the atmosphere and observe solar extreme ultraviolet and X-ray radiations, which do not reach the Earth's surface due to absorption in the atmosphere (Fig. 1 shows the solar flux distribution above the atmosphere). A magnetograph was devised for studying the solar magnetic field outside sunspots. An International Geophysical Year (IGY, 1957–1958) was planned and more than 20,000 scientists at more than 2,000 locations obtained synoptic observations of dozens of solar and terrestrial phenomena. Following the work of Tousey and his group (details in Tousey, 1986) in obtaining spectrograms in rocket flights, Friedman (1981) developed electronic methods of detection, which were sensitive and rapid, and the measurements could be relayed to the ground during flight via the rocket's telemetry system. His study of solar flares by means of rockets conclusively demonstrated that solar X-ray bursts caused shortwave fadeouts. (Fig. 2 illustrates the processes occurring on the Sun during a solar flare). Also, since the nuclear reactions powering the Sun involve emissions of neutrinos, some scientists thought of detecting these particles (which were theoretically expected to be traveling outward from the Sun's core at the speed of light) by their ability to transmute the nuclei of chlorine 37 into argon 37. In the Homestake Mine of South

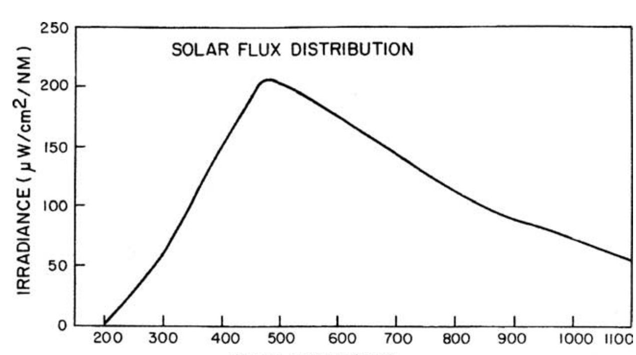

Fig. 1. Solar spectrum above the terrestrial atmosphere.

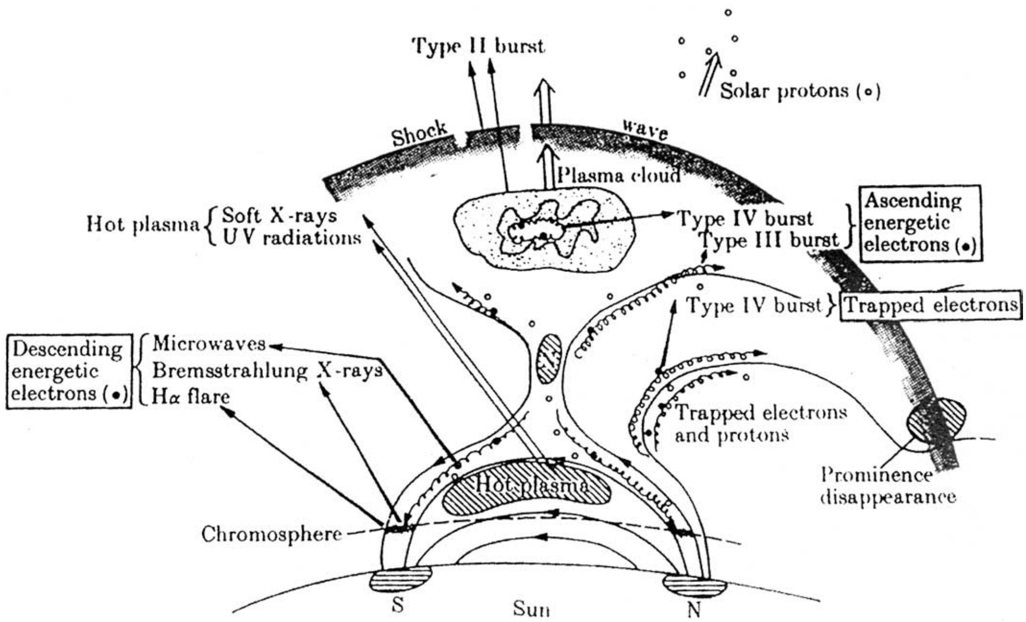

Fig. 2. Major processes on the Sun during a typical solar flare (Piddington, 1969).

Dakota, Davis put his detectors in 1967, but the rate turned out to be very low, far less than theoretically expected, perhaps requiring a major revision in stellar or neutrino theory (Bahcall, 1969).

The most important contribution to solar physics during the IGY was an indirect one, the launching of the soviet satellite Sputnik on October 4, 1957. Partly political, the launching of Sputnik stirred up considerable scientific activity in 1957–1958, with scientific instruments placed in orbit by the Soviet Union on Sputnik 1, 2, and 3 and by USA on Explorer 1, 3, and 4, Vanguard 1, and Pioneer 1. In October 1958, the US government made operational a civil agency named National Aeronautics and Space Administration (NASA), which announced soon that it was ready to help other nations to put instruments (or even complete scientific satellites) into orbit. This encouraged space research in many countries and by 1975, scientists in more than twenty nations had joined United States and Soviet Union in studying natural phenomena with the aid of spacecraft. Meanwhile, American and Soviet programs were getting more and more sophisticated, with larger spacecrafts going on longer journeys and communicating more rapidly and reliably with ground stations, besides promoting greater support to scientists using traditional approaches and cultivating closer ties between them. For observations of solar electromagnetic radiations, many satellites were launched (OSO 1, 3, 4, 6; SKYLAB; AEROS A, B; AE-C,E; SOLRAD 11; PROGNOZ 7-10; SMM; San Marco 5; PHOBOS 1,2; YOHKOH; CORONAS 1, INTERBALL 1; ELECTRO; SOHO; TIMED; ISS; GOES, details in Tobiska et al., 2000) and many of the ground observatories had improved instrumentation (e.g., Kitt Peak's McMath Solar Telescope). Tobiska et al. (2000) and updates have produced an empirical solar irradiance model, which can be used by workers as input for studying terrestrial effects. The journal *Solar Physics* established itself as a thriving international forum for the solar physics community. In recent years, funds have also gone for nonsolar astrophysical missions such as International Ultraviolet Explorer, Einstein High Energy Astronomical Observatory, Infrared Astronomical Satellite, Hubble Space Telescope and Chandra. The Challenger disaster of January 1986 proved a big setback for spacecraft launching programs as well as ground-based solar observing programs. However, a part of this loss has been compensated by improving the precision, versatility and reliability of the payloads and acquiring a new generation of high-resolution solar telescopes and upgrading auxiliary instrumentation as new technologies become available.

An important development since World War II was solar radio astronomy, mainly due to the lead of a group in Sydney, Australia, where Pawsey (1946) and his team showed that particular spot groups were associated with enhanced solar radio emission, but there was a steady background component also which indicated a coronal temperature of 600,000–1,200,000 K. Since then, many radiospectrographs have been operative in different parts of the world, supplying very useful information for studies of solar phenomena like solar flares. Synoptic radio observations of the Sun started in Canada in November, 1946, when Covington used a 4-ft reflector from a Type IIIC Gun Laying radar system to start recording the solar flux at 3-cm wavelength.

In 1947, Covington's landmark measurements developed into a regular observing program at 10.7 cm. The daily flux was measured in Ottawa at Algonquin Radio Observatory until June 1991, when the program was moved to Penticton at Dominion Astrophysical Observatory, three time zones west, where it continues today. There has been some controversy about whether the microwave flux from active regions is due to thermal bremsstrahlung or gyro-resonance emission, which would then indicate whether the source of emission was the optically thin corona or optically thick sunspots. Spatially resolved spectra in the cm-wavelength range indicate that gyro-resonance emission (with peaked spectra) usually dominates the flux from active regions, while thermal bremsstrahlung emission (flat or rising spectra) comes from plage regions displaced from spots.

A solar phenomenon of considerable importance, namely CME (Coronal Mass Ejections) was identified by Tousey (1973) in the OSO-7 data. During the most active phase of the solar cycle of ~11 years (solar maximum), the solar activity is dominated by flares and disappearing filaments, and their concomitant CMEs. The fast CMEs coming from the Sun into the interplanetary space are the solar/coronal features that contain high magnetic fields. This is discussed further on in details.

3. Solar wind

Even before 1950s, many scientists suspected that the Sun might be sending corpuscular matter into space with speeds large but much lesser than that of light (Kiepenheuer, 1953). Strong aurorae and some geomagnetic disturbances seemed to recur in 27 days (solar rotation period) and were stronger at the terrestrial poles, indicating some sort of channeling of charged particles by the geomagnetic field. Even in quiet periods, there seemed to be some solar inputs. Biermann (1951, and later papers) precipitated this thinking by suggesting that the comet tails always pointed away from the Sun because of impinging solar corpuscular material (100–1000 ions and electrons at speeds of 500–1000 km/s) all the time, and solar radiation pressure was grossly inadequate to produce this effect. Not many people agreed with Biermann. The famous solar-terrestrial physicist Sydney Chapman (1957) claimed that the Sun had a static atmosphere (just like the Earth) but so large that the outer edges of its corona could engulf and affect the Earth. However, Parker (1958, 1959, and later papers) at the University of Chicago examined this issue and found that the atmosphere of the Sun was not only not static but highly dynamic and could have solar efflux of the same order as indicated by Biermann. Parker termed the efflux as "solar wind", attributed it to the expansion resulting from coronal temperatures of ~2 million K over an extended region around the Sun, and expected that the expanding gas would draw magnetic field lines out of the corona far into the solar system and, because of the solar rotation, the resulting interplanetary field would have a spiral pattern in the Sun's equatorial plane. As a mechanism for the high temperatures of the corona, Parker suggested that hydromagnetic (Alfven) waves propagating upward from the photosphere dissipated their energy in the coronal plasma by magnetically accelerating the fastest protons encountered there to still higher velocities.

Parker's theory of solar wind got a very lukewarm reception. Chapman (1959) was not certain that ejection was continual over the whole Sun. Chamberlain (1960) criticized Parker's idea as arbitrary and proposed an alternative model which needed a much lower velocity for the expanding plasma – a solar breeze. Only Thomas Gold (1959) seems to have appreciated the theory and made his own conjectures about the behavior of plasma and magnetic fields in the solar system. Parker realized that a confirmation of his theory could come only through experimental observations by satellites. The first such evidence of a solar wind came from the Russian group of Gringauz et al. (1960) who reported observations from Lunik 2 (launched in September 1959), indicating a flux of high-speed ions of $\sim 2 \times 10^8$ ions/cm^2/s, but their speed and direction were not known. This was followed by the American experiment on Explorer 10 (launched in March 1961) which rose above the Earth's night side in a highly eccentric orbit with an apogee of 240,000 km and probably never reached the undisturbed interplanetary medium, but reported a flux of $\sim 4 \times 10^8$ ions/cm^2/s (double that of Lunik 2) with speeds of 120–660 km/s (generally away from the Sun), yielding plasma densities of ~6–20 protons/cm^3 (Bridge et al., 1962). More convincing results were obtained by Mariner 2 (launched in August 1962), where data for 104 days indicated a continuous plasma flow but with peaks of high activity and quiet periods. The velocities ranged between 400 and 700 km/s but occasionally exceeded 1250 km/s (Neugebauer and Snyder, 1962), always away from the Sun, and the spectra showed two maxima indicating the presence of helium nuclei as well as protons. Soon after, Snyder et al. (1963) reported that the solar wind contained high-speed corpuscular streams with velocities of 600–700 km/s, recurrent at a 27-day (solar rotation) period and correlated with the recurrent peaks in geomagnetic activity, yielding a linear relationship between solar wind velocity and geomagnetic index (a clear Sun–Earth link). These streams did not seem to arise in a hydrodynamic expansion of a homogeneous solar corona but came instead from long-lived local regions in the corona, which were abnormal in some respect. In subsequent years, several satellites have been used to study the interplanetary plasma parameters of solar wind.

An important discovery during this period was that of a magnetic sector structure in the solar wind, where the interplanetary space in the equatorial plane around the Sun seemed to be divided into alternate sectors of magnetic field directions ‘away from the Sun’ and ‘towards the Sun’ (Ness and Wilcox, 1965). Fig. 3 illustrates the sector structure. Wilcox (1986) suggested that the distribution of large, long-lived unipolar regions in the equatorial latitudes in the photosphere mapped out in the interplanetary field as sectors. His student Schatten developed a ‘source surface model’ wherein the complex field of the photosphere was smoothed out as a sector-like pattern at a thin region (source surface) in the corona about 0.6 solar radii above the photosphere, and the pattern was carried out in interplanetary space by the solar wind (Schatten et al., 1969). However, the sector structure has now a more plausible explanation in terms of a ‘two hemisphere model’. The magnetic fields which originate in the northern hemisphere of the Sun point in one direction (inward or outward) while fields originating in the southern hemisphere point in the opposite direction. The boundary between the two magnetic hemispheres consists of a thin neutral sheet, in which the magnetic directions are not consistent. The neutral sheet is slightly warped, so that it does not lie quite flat in the plane of the Earth’s orbit. As the Sun rotates, the sheet also turns, so that the Earth is alternately on one side of the warped region or the other. As this happens, satellites near the Earth observe the change in the direction of the interplanetary magnetic field as the sector boundaries pass the Earth.

Several decades ago, Bartels (1932) noted the 27-day recurrence tendency in geomagnetic storms but did not

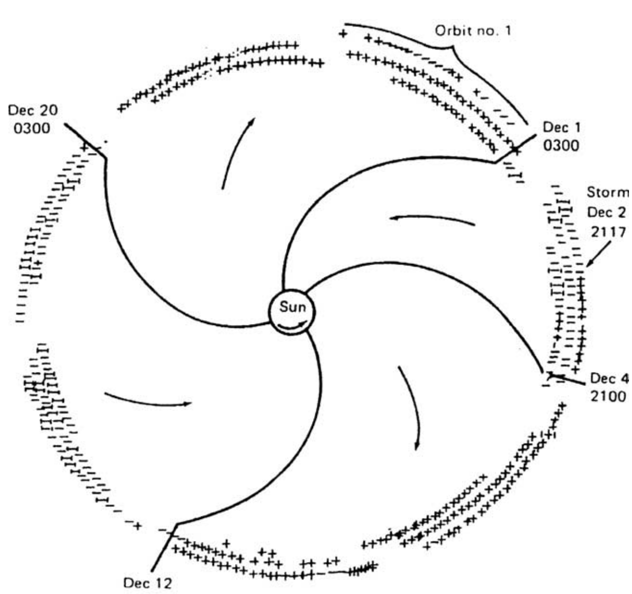

Fig. 3. Spiral and sector structure of the interplanetary magnetic field (Ness and Wilcox, 1965).

find any associated striking features on the Sun, and hypothesized invisible M regions as the possible sources. Ness and Wilcox (1965) identified the M regions to unipolar magnetic regions. The recurring geomagnetic storms are found to coincide with streams that are much faster than the normal solar wind. By comparing the arrival times of these high-velocity streams with pictures of the Sun’s corona taken by Skylab X-ray telescopes on known dates, the high-speed streams were traced to parts of the corona, which emit no X-rays, the so-called coronal holes. The temperatures and densities of coronal holes are much lower than those of other parts of the corona. Investigations show that in the holes, the magnetic field has no loops, but extends directly out into the solar wind. It is not yet known how and why coronal holes form, but they are known to be a major source of the solar wind. Two apparently long-lived coronal holes exist at the north and south poles of the Sun, and these contract and disappear as the solar activity increases and reaches its maximum (during the solar maximum, short-lived coronal holes appear at lower latitudes). It may be that much of the solar wind that leaves the Sun originates in these polar coronal holes. Long-term solar wind velocity variation does not completely correlate with that of sunspots, nor with the variation of geomagnetic activity.

4. Magnetosphere and geomagnetic storms

The geomagnetic field is basically dipolar and should fall off with distance r as r^{-3} in the equatorial region. However, the solar wind exerts a pressure and the field is compressed on the sunward side. Early satellite measurements showed that the geomagnetic field was confined to what is known as the ‘magnetosphere’, snub-nosed like a bullet on the sunward side up to about 10 Earth radii, and stretched far back to several tens of Earth radii in the magnetotail, in quiet time solar wind. When solar flares occur, apart from the production of energetic particles (the so-called solar cosmic rays), material is ejected outwards and these CMEs produce shocks which propagate in interplanetary space with high solar wind pressures. If the Earth encounters these, the sunward boundary of the magnetosphere may be compressed to even up to 7 Earth radii, but solar wind cannot penetrate the magnetosphere easily and is mostly diverted to the tail side. However, it was noticed that only on certain occasions, the solar wind penetrated the magnetosphere from the tail side and the necessary condition seemed to be a negative Bz component of the magnetic field in the shocks. The reason for this remained a mystery till Dungey (1961) gave an explanation. As the geomagnetic dipole field is stretched in the magnetotail, a neutral sheet is formed, with geomagnetic field away from the Earth above the neutral sheet and toward the Earth below the neutral sheet. At the end, in a small region far away from the Earth, the field is still north-south. If the field in the interplanetary shock has a component (negative Bz), which can neutralize the geomagnetic field, a neutral point is formed and solar wind gets an entry into the magnetosphere. Low energy particles spiral around the stretched geomagnetic field lines and impinge on the terrestrial atmosphere in the polar regions, causing enhanced aurora. Higher energy particles rush towards the Earth but are diverted around the Earth in circular orbits in the equatorial plane and cause large geomagnetic field reductions (Dst, storm-time disturbance depression of several tens of nT), which recoup slowly when the Earth comes out of the shock region and solar wind input stops. Thus, for geomagnetic storms to occur, two conditions are necessary. Firstly, the Earth should enter a disturbed region, and secondly, the region should have a magnetic field component (negative Bz), which can neutralize geomagnetic field in a small region in the magnetotail and create a neutral point, which facilitates entry of solar wind into the magnetosphere. If the region has a shock, a SSC (Storm Sudden Commencement) is produced. If the shock is not produced by a CME associated with a solar flare but is produced by a (fast) stream- (slow) stream interaction, the same conditions are still applicable. If there is no shock, there will be no SSC and only a smooth decrease in geomagnetic field will occur. Fig. 4 gives synoptic views of: (a) flare-associated 'driven' shock and (b) stream interface, while Fig. 5 shows the magnetospheric Sun-side compression and tail-side elongation under the influence of solar wind.

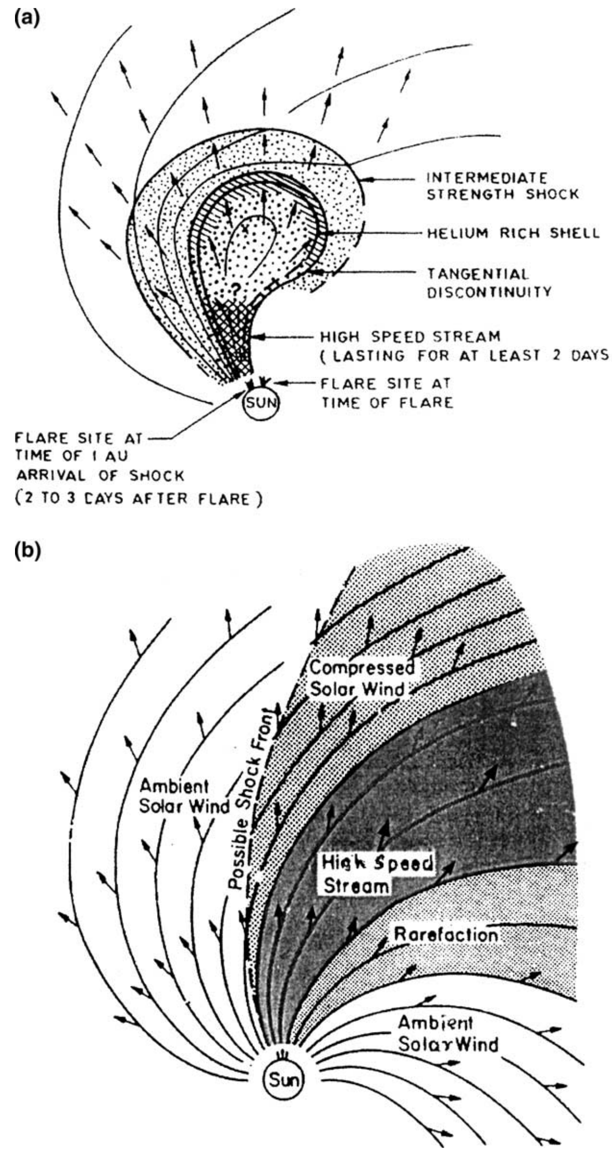

Fig. 4. Synoptic views of: (a) flare-associated 'driven' shock, and (b) stream interface (Hundhausen, 1972).

Before the space age, interplanetary flows (plasma moving at high speeds from the Sun to the Earth) affecting geomagnetic field were called by various names: clouds, plasma clouds, turbulent clouds, nascent streams, flare streams, magnetic tongues, jets, magnetized plasma clouds, bottles, and bubbles. After in situ measurements by spacecrafts were available, the flows have been called: post shock flows, drivers, transients, plasma clouds, flare ejecta, coronal mass ejections (CME), interplanetary CMEs (ICMEs), ejecta and magnetic clouds. The American Geophysical Union (AGU) has prepared an index set which defines these phenomena. Burlaga et al. (2001) used the term "ejecta" for the interplanetary flows, and "CME" for coronal mass ejections that can be seen moving through the corona with a coronagraph. They identified "fast ejecta" (transient, non-corotating flows moving past the Earth during a day or more, with maximum speeds exceeding 600 km/s) in the ACE observations during 1998–1999, the ascending phase of solar cycle 23. They found 4 "magnetic clouds" (local magnetic structure of a flux rope) and 5 "complex ejecta" (disordered magnetic fields). All the magnetic clouds were mostly associated with a single solar source and caused geomagnetic storms, while complex ejecta could have multiple solar sources, and 3 of the 5 complex ejecta did not produce geomagnetic storms. Farrugia et al. (2002) used ACE and Wind data for the first strongly geoeffective interval during 1–4 May 1998 and found a configuration of a compound stream made up of an interplanetary coronal mass ejection (ICME) containing a magnetic cloud and being trailed by a hot, faster flow. Incidentally, there are stream–stream interactions (fast flows impinging upon slower flows), which create shock fronts in corotating high-speed streams (Belcher and Davis, 1971), which give recurring geomagnetic storms (higher Kp indices at ~27-day intervals).

An interesting aspect of the interplanetary parameters is the idea of what is known as "Space Weather" or Space Meteorology, first introduced by Gold (1959)

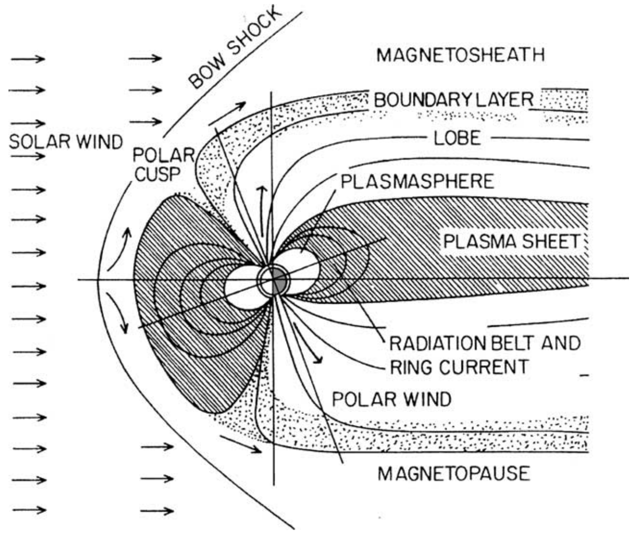

Fig. 5. Magnetosphere, compressed on the sunward side and elongated on the tail side.

as a counterpart of Meteorology on Earth. Since geomagnetic storms having Kp index exceeding 6 (Dst < −150 nT) affect satellites as well as terrestrial installations like communication systems, power grids, etc., there is great interest in detecting the increases in interplanetary parameters, if possible, beforehand. The present state of prediction schemes is discussed by Gonzalez et al. (2004) and shows some promise of knowing the arrival of a storm with an antecedence of several hours, particularly by using the lateral expansion speed of a CME (Dal Lago et al., 2004). Another interesting possibility is through the study of radio flux measurements. Using the delays in increased radio flux at different frequencies, one can calculate the speed of the solar eruptions up through different heights in the solar atmosphere, and thus estimate the time of the arrival of the shock at the Earth, with antecedence of several hours (Boteler and Tapping, 2004).

5. Ionospheric and thermospheric effects of solar variability

The thermosphere lies above approximately 90 km, the point at which the mesopause is defined. Above this height, the temperature changes from decreasing with height to increasing with height. The thermosphere ends at the boundary with the exosphere, approximately 500–700 km, where atoms can escape freely from the atmosphere. The thermosphere is heated by solar UV and EUV wavelengths where photons are absorbed by atoms and molecules leading to their dissociation and ionization. This photoabsorption process effectively transfers the energy of a photon into kinetic energy of an atom or molecule, the source of heating. The effect is direct, i.e., more photons during high solar activity lead to more heating. From solar minimum to maximum, the temperature at the top of the thermosphere (700 km) (the exospheric temperature) can vary from 900 to 1500 K. Night-to-day differences are of the order of 30%. Since satellites can have orbits as low as about 120 km, the lower thermosphere can have a dramatic effect on satellite drag and the increased density causes satellites to lose altitude. Although the atmosphere densities at these altitudes are still a vacuum from a human perspective, from a satellite perspective the density is very significant, since a satellite is traveling thousands of kilometers per hour and the integrated resistance becomes significant very quickly. Satellites lose altitude at different rates depending on their areal cross-section, altitude, and mass as well as the varying atmospheric density. The thermospheric variations represent a complex nonlinear response to changing fluence of solar radiative emissions (visible, UV, X-ray emissions, directly via radiative transfer), as well as charged particles and electric/magnetic fields (indirectly via electrodynamics of the ionosphere, Roble, 1996). It seems the current atmospheric neutral density models are inadequate and efforts are being made to develop new models of the thermospheric density response to solar and geomagnetic activity (Sangalli et al., 2003).

The ionosphere contains charged particles (ions and electrons) that are formed from solar ionizing radiation, predominately the solar EUV and X-ray irradiances. To a large degree, photoionization of oxygen and nitrogen, in combination with photochemistry, produces the ions and electrons in the E and F regions. Usually, the assumption is made that the ionosphere is neutrally charged, i.e., that there are equal numbers of electrons and ions. The electron density is low at 50 km, rises rapidly to a maximum between 100 and 250 km (the exact altitude of the peak layer is dependent on solar activity), and then gradually decreases over thousands of km. The regions and layers of the ionosphere are roughly: 50–90 km, D; 90–(120 to 140) km, E; above (120–140) km, Fl, F2. One dramatic effect of the ionosphere is how it affects radio communication. Depending on solar activity, some radio frequencies are totally blocked, while others are enhanced under disturbed conditions; this can change by the minute, particularly during large geomagnetic storms that come from the solar wind carrying charged ions. Another interesting effect is that spacecraft experiences "charging" as a result of the large numbers of available electrons that become attached to the spacecraft and, under the right conditions, electrical arcs can occur within the satellite that sometimes damage electronic components.

When solar flares occur, ionospheric number densities may increase causing SFE (solar flare effects) but these are short-lived (increase in a few minutes, recovery in a few hours). Major effects occur when low energy particles precipitate in the auroral regions, an 'auroral electrojet' is formed, joule heating occurs, and ionization travels towards lower latitudes. This occurs preferentially along the geomagnetic field lines, which are not parallel to the ground but are rising. Firstly, the ionospheric heights increase, and secondly, the particles enter in regions of different, altitude-dependent, loss processes. Thus, ionospheric storm effects occurring at different locations can be very complicated, depending considerably upon the local time when the geomagnetic storm commenced (Kane, 1973; and many other later papers). Hence, predictions can be hazardous. However, for long-term changes, both foF2 and thermospheric temperatures increase in parallel with the sunspot activity.

On short-term time scales, effects of solar flares on magnetospheric radiation belt particles at 1000–6000 km can bring down a torrent of particles affecting the ionosphere and brightening auroras. High energy solar protons from CMEs can enter directly into the Earth's atmosphere, warm the outer layers of the polar atmosphere (above 50 km) by several degrees, and create NOx compounds which can deplete ozone and cause lesser UV absorption and hence, cooling of the atmosphere. Effects of solar flares on the thermosphere and the ionosphere as represented by a coupled thermosphere–ionosphere model have been discussed in detail by Viereck et al. (2003).

6. Mesospheric and stratospheric effects

Climate change in the mesosphere: tropospheric warming, due to increased greenhouse gas concentrations over the last 150 years, is often termed the "greenhouse effect". However, there is also a middle atmosphere manifestation of the greenhouse effect: enhanced *cooling* in the stratosphere and mesosphere. Modelling studies indicate a maximum cooling response in the high-latitude mesosphere. Therefore, the ability to use the hydroxyl layer to measure the temperature in the Antarctic mesosphere, makes the OH spectrometer an ideal instrument for monitoring middle-atmosphere temperatures for studies of climate change. Some reported observations suggest that pronounced cooling, (up to 7 K/decade) in excess of model predictions, has already taken place.

For the mesospheric region, Clemesha et al. (1997) reported long-term and solar cycle changes in the atmospheric sodium layer, while Jacobi (1998) reported on the solar cycle dependence of winds and planetary waves in the mesopause region. In general, the connection in the mesopause region is weaker. However recently, Clemesha et al. (2005) and Scheer et al. (2005) reported solar effects in OH rotational temperatures and atomic oxygen related airglow brightness in low and middle latitudes in South America. Short-term effects are small or erratic. In the stratosphere, there is a naturally formed ozone layer and it has a small (a few percent) solar cycle effect, which may get reflected in the filtered ultraviolet in certain wavelength bands. Of particular interest is the effect on UVB, which is harmful to human skin. The changes in UVB due to solar cycle changes of ozone are rather small. A greater hazard is due to the depletion of ozone by man-made chlorofluorocarbons, as this may increase the UVB doses considerably and cause skin cancers.

Energetic particles from the Sun can strongly influence the chemical composition of the middle atmosphere, which may change the radiation budget and temperature in this region. A numerical simulation of the response of ozonosphere to the solar proton event (SPE) of July 2000 (one of the strongest near solar maximum of cycle 23) showed strong ozone depletion in the mesosphere and stratosphere after this event (Krivolutsky et al., 2005).

Stratospheric responses to solar ultraviolet variations have now been observed on both the solar rotation and the solar cycle time scales (Hood, 2004). Although the observed responses are qualitatively consistent with theoretical expectations, there are important quantitative differences. This is true especially on the solar cycle time scale in the lower stratosphere where observed responses are much larger than expected from existing models.

The 27-day ozone response in the tropics has been accurately measured and is in good agreement with recent stratospheric model calculations. There is also good evidence for a response of tropical upper stratospheric temperature on this time scale. However, the derived positive temperature phase lags are significantly larger than expected from models that consider only radiative and photochemical processes. It is therefore inferred that a dynamical component of the response exists. Substantial evidence exists for a significant solar cycle variation in both the upper and the lower stratosphere. The unexpectedly large solar cycle signal in the lower stratosphere may be caused by the apparent ability of weak solar UV forcing in the upper stratosphere to influence the selection of preferred internal modes, or types of circulation, in the winter stratosphere. In conclusion, some progress has been made during the last decade toward understanding the response of the stratosphere to solar cycle changes in UV flux. However, remaining differences between observations and model simulations indicate that further work in both observational and modeling areas is needed before a full understanding will be achieved. By implication, current general circulation model simulations of the effect of solar UV variability on climate change must be regarded as provisional. More realistic simulations must await a more complete knowledge of the processes that lead to the observed stratospheric effects and how these effects are transmitted to the troposphere.

7. Climatic changes

The study of the effects of the short-term variability of solar radiation on terrestrial climate has been very copious and has a long history (Pittock, 1978). However, the conclusions have been mostly uncertain and sometimes confusing. Attention has been paid to: (a) radiative forcing (Lean and Rind, 1999, and references therein); (b) magnetospheric Relativistic Electron Precipitation (REP) events causing ozone depletion (Lastovicka, 1991) and abrupt changes in atmospheric circulation (Bucha and Bucha Jr., 1998); (c) cosmic rays (controlled by solar magnetic field extension in the heliosphere and showing an 11-year cycle) affecting global cloud coverage (Tinsley, 2000), (d) ionospheric ground electrical circuit variability by controlling cloud microphysics (Baker, 1986), and through their strong connection with sudden commencement storms (Bochnicek et al., 1999). Recently, one more mechanism has been suggested, namely, when solar wind energy is deposited in the auroral electrojet during storms, atmospheric gravity waves are generated. If these are transmitted downward and get amplified by wind shears or seeding instabilities that generate gravity waves in the mid-latitude troposphere, cloud formation may occur and cause weather changes (Prikryl et al., 2003).

The contribution of solar variability to climate is small and on short-term time scales, there are major earthly effects like those of greenhouse gases, volcanoes, sulfate aerosols, El Niños and probably many others (unrelated to solar activity) which are overwhelmingly larger than the solar effects, which can therefore be detected (if at all) by sophisticated statistical analyses. In rainfall series, an 11-year signal is often found for some locations, but these are not stationary and are not phase locked with sunspot activity (Lean and Rind, 1999). However, Reddy (2001) reported an 11-year cycle in the equatorial lower stratosphere, Alaskan climate, Indian summer monsoon, and Reddy and Karim (2003) presented evidence showing a modification of the solar cycle effect by phases (easterly or westerly) of the stratospheric wind QBO (see also Labitzke and van Loon, 1990).

Total Solar Irradiance (TSI) has been measured accurately during the last two decades and shows a small (~0.1%) variation over the sunspot cycle, and there is a great controversy whether such a small change can cause significant climatic changes. Whereas direct effects of visible solar radiation may be negligible, indirect effects through cosmic rays, etc., which have a large solar cycle variation, may be substantial. Also, the solar UV flux has a considerable solar cycle fluctuation and through photochemistry, may influence stratospheric ozone and therefore, stratospheric temperature. On a long-term time scale, the global warming seems to have increased from the late 19th century to around 1940, decreased up to the mid-1960s, and increased substantially thereafter. Lean and Rind (1999) have looked carefully at the historical record of the sun's varying activity levels, including direct observations of solar radiation over the last 20 years and indirect evidence of solar activity implied through the study of ice cores and tree rings (Eddy, 1976). Lean and collaborator Rind made simulations with computer models of climate change in response to changes in solar radiation during the past 400 years. They then used the model results to compare with both pre-industrial and current climate change trends to determine the role of the Sun in the heating on the Earth. The general conclusion of their study is that the Sun may have played a dominant role in pre-industrial climate change (from 1600 to 1800, for example) but it has not played a significant part in long-term climate change during the past few decades. It is furthermore unlikely that the Sun accounted for more than half, at most, of climate change from 1900 to 1970. Stott et al. (2000) developed a computer model which indicated that whereas anthropogenic emissions alone could explain the rapid rise in temperatures in the past 30 years and that solar variation alone could have caused the warming observed during 1910–1940, a model including both these causes could explain only up to 60% of the variations of the entire century. Lawrence et al. (2000) have developed an "extremely crude model" of three interrelated equations to stimulate the flow patterns in the atmosphere at middle latitudes. The model calculates the average speed of the westerly flow of winds as a function of latitude and exhibits chaotic behavior, where even small changes in the inputs to complex systems can cause large changes in the answers. The model's calculations produce correlations that appear during the early phases of a simulation, disappear later in the simulation, and then reappear as anticorrelations. This matches the past behavior of the solar cycle. Between 1860 and 1920, cooler temperatures occurred when sunspot numbers were large. From the 1920s to the 1960s, there was no clear correlation between sunspot numbers and temperature. But after 1960, increased sunspots correlated with higher temperatures. Finally, Lawrence's model allows the Northern and Southern Hemispheres to fluctuate independently of one another and to have different correlations to the solar variation, as has been observed. Incidentally, the comparisons made by Duhau (2003) show that the observed temperature decrease during 1920–1960 (when sunspot activity was still rising) can be reproduced if a correlation analysis includes a geomagnetic SSC index (product of the magnitude and the duration time of a storm sudden commencement, averaged over an year). Georgieva et al. (2003, and references therein) have noted that the correlation between the Earth's surface temperature and sunspot activity in the 11-year solar cycle depends on the period studied and changes sign in consecutive secular Gleissberg cycles (~80 years), and this relationship depends upon the solar activity asymmetry, positive when the northern solar hemisphere is predominantly more active, and negative when the southern solar hemisphere is predominantly more active. The two solar hemispheres rotate differently and the interplanetary magnetic field at the Earth's orbit is related to the differential rotation of the more active hemisphere. Also, the two hemispheres have different magnetic helicities, which are carried to the Earth by magnetic clouds preserving the helicity of the source region of their origin. The reaction of the terrestrial atmosphere to the arrival of the magnetic clouds depends on the helicity of these clouds, in addition to a stratospheric QBO phase effect. Incidentally, the N–S asymmetry of solar activity seems to have a QBO of its own (Badalyan et al., 2003).

In short, Sun–climate relationship is very complex by itself and meteorological changes by other effects such as of greenhouse gases, volcanoes, sulfate aerosols, El Niños and probably many others, which are overwhelming larger than the solar effects, can complicate matters still further. That is why no single effect is seen invariably and consistently, and for the same reason, accurate predictions are not possible. Incidentally, some terrestrial phenomena apparently unrelated to solar activity may not be unrelated completely. Volcano activity displays no 11-year periodicity, but 21-year running averages seem to indicate that volcanic activity is generally lower in periods of prolonged maxima of solar activity (Strestik, 2003), and their spectra show similar periodicities (200–215, 100–105, 80–90 year). If true, a connecting mechanism needs to be discovered. Similarly, a possible connection between El Niño events and solar activity reported by Landscheidt (2000) needs further scrutiny.

8. Present status

8.1. Solar physics

The origin of all solar activity is in the convective zone (immediately below the photosphere), and helioseismology has provided considerable information about the interior structures and dynamics, from the global dynamo to small-scale flow associated with solar flares (Kosovichev, 2003). Solar oscillations have typical periods of 3–10 min with maximum power at about 5 min. These are excited near the surface. The f-modes (surface gravity waves) propagate in a thin layer just beneath the solar surface and are useful for measuring the solar seismic radius, while the p-modes (acoustic waves) propagate in the deep layers of the Sun and are finally reflected back. Two regions, the tachocline and the upper convective boundary layer are critical for understanding solar variability. Both regions have strong rotational shears and provide evidence for a 1.3-year periodicity but no indication of an 11-year periodicity. Sunspots as cool objects appear to be only 4–5 mm deep, but accumulate significant heat in the deeper layers and form converging downfalls. Sunspots have a tree-like magnetic structure. (Mechanisms of sunspot formation and stability are not yet understood). Large active regions are formed as a result of multiple flux emergence. Flow maps show that in the subphotosphere, there are divergent supergranular flows and strong converging flows in magnetic regions, but there is remarkable multiple-scale reorganization on the larger and global scales. There are zonal flows, which migrate to the equator (reason not yet fully understood) and meridional flows from the equator to the poles. Bumba (2003) mentions that besides the 11-year and 22-year cycles in solar activity, there exist several modes of cyclic variations of lesser periodicities (QBO 2–3 years, 1.3 years, 150–160 days) and all of them seem to be related to the regularities in the appearance and distribution of the magnetic flux in the photosphere by its more or less spatial grouping through the local magnetic fields in active longitudes, and temporal grouping in the formation and development of complexes of activity. However, there is also a suggestion that these may be harmonics or subharmonics of a certain basic period.

Another interesting observation relates to the multiple peaks (mostly two) in solar activity at sunspot maximum. In cycle 23, there were two distinct peaks, one near July 2000 and another near February 2002 (separation about 20 months). The relative magnitudes of the first peak with respect to the second peak are different for different solar indices. For sunspots, the second peak was lower than the first peak by ~4%, but the second peak was higher than the first peak by ~3.5% for solar EUV (26–34 nm) and higher by ~10% for 2800 MHz radio flux and for Lyman alpha (Kane, 2003). These differences need explanation. They may be related to the way the sunspot number is computed.

CMEs and solar flares are two important phenomena responsible for solar emissions entering the interplanetary space. During the last few years, copious observations of CMEs were possible. Using the SOHO/LASCO coronagraph, Gopalswamy et al. (2003) reported the results of a study of nearly 7000 CMEs, which occurred during 1996–2002. The peaks of CMEs and sunspot number were almost two years apart and the CME mean speeds doubled from sunspot minimum to maximum. High latitude CMEs were intimately related to the solar polarity reversal during solar maximum, and polarity reversal seemed to be an energetic process involving the release of large amounts of energy. Both sunspot activity and high latitude CME activity were high at sunspot maximum. Maricic et al. (2003) studied the initiation and development of two CMEs and both show clearly a three-part structure already at low heights during the initial gradual rise in the pre-eruptive phase. Many other details are given.

A major lacuna in solar physics is the failure of solar flare theories to account for the fact that the total power and the number of particles required to explain the emissions cannot be supplied by the active region. Simnett (2003) invokes a global view where an erupting magnetic structure plays the central role and the active region plays a minor role. Magnetic reconnection in the high corona gradually pumps up the erupting structure with mildly energetic particles, mainly protons. Finally the stability of the structure is destroyed, and it erupts, dumping the particles into the evolving active region, where they are reaccelerated to produce the high energy flare protons and other emissions. The energy and matter supplied by the erupting structure is sufficient to overcome the active region deficit.

8.2. Interplanetary disturbances and their magnetospheric response

Only 1–2% of the nearly 7000 CMEs studied by Gopalswamy et al. (2003) during 1996–2002 were geoeffective. Those resulting in Solar Energetic Particle (SEP) events need to drive a shock that accelerates particles, and hence, need to be fast and wide. The storm-causing CMEs need to be directed towards the Earth and must contain a southward component Bz of the magnetic field. Halo CMEs occurring on the solar disk (those which appear to surround the occulting disc of a coronagraph) and fast and wide CMEs are important from the point of view of space weather. Presently, considerable effort is made in studying the relationship between parameters of geomagnetic storms, e.g., Dst magnitudes, and parameters of halo CMEs, notably magnetic cloud speeds (e.g., Gonzalez et al., 2004). The principal interplanetary parameters controlling the magnetospheric response are the solar wind ram pressure and the Interplanetary Magnetic Field (IMF) magnitude and direction. Feldstein et al. (2003) examined a two-stream solar wind interval (two interplanetary CME events) during May 1–7, 1998, modeled the magnetospheric response to these events, and compared with satellite data. For the intense storm of May 4, 1998, they estimated the disturbance fields as: −208 nT due to DR (Disturbance due to ring current), 112 nT due to DCF (Disturbance due to Chapman-Ferraro magnetopause current system), and −161 nT due to DT (Disturbance due to tail current system). They note that these currents significantly modify the magnetospheric geometry and size and must be included for any accurate magnetic field representation during storm periods. An interesting test of large changes in magnetospheric geometry came when during May 10–12, 1999, the solar wind almost disappeared. While the wind velocity maintained its normal value of ~360 km/s and the magnetic field was ~6 nT, the number density dropped below l/cm^3 and the dynamic pressure dropped below 0.1 nPa. The bow shock along the Earth–Sun line, normally at a distance of ~10 R_E, reached a maximum value of 53 R_E (Youssef et al., 2003, and references therein).

8.3. Climate

Whereas several mechanisms are suggested for solar effects on climate, all these seem to be mostly of academic value, as few indicate substantial effects like those in Labitzke and vanLoon (1997) and Labitzke (2001). Ramaswamy et al. (2001) reviewed the stratospheric temperature data from various sources and found that the stratosphere has, in general, undergone considerable cooling over the past 3 decades, and the major radiative factor responsible for this is the depletion of stratospheric ozone, though some contribution from the increases of greenhouse gases is also expected. Superposed on this trend is a solar cycle variation of about 1 K during a solar cycle. At the SORCE Science Meeting at Sonoma, Hameed et al. (2003) suggested the following possibility. ''Variations in global heating rates and circulation cause changes in the intensities and the morphologies of the atmospheric centers of action (such as the Aleutian Low and the Hawaiian High). In turn, these systems influence atmospheric and oceanic circulations over their respective domains. The centers of action therefore may be considered to act as bridges between variations on the global and regional scales, and could provide a viable link between small magnitude solar activity changes and large changes in local climate. It is known that solar activity induces changes in UV radiation and stratospheric ozone. The primary response of the atmosphere to this direct forcing is in the zonal circulation in the stratosphere. This circulation change induces changes in the centers of action as stationary wave nodes. These changes may be small. However, the changes induced by a center of action in regional circulation and clouds feed back to the center of action. As a result, significant changes in regional climate are observed associated with the solar cycle''. In another presentation at Sonoma, Rind (2003) said ''We used various climate change experiment simulations from the Goddard Institute of Space Studies (GISS) global climate/middle atmosphere model to investigate the impact stratospheric perturbations have on the troposphere with emphasis on solar forcing. Atmospheric radiation, advection, stability influences and wave-mean flow interactions allow the stratospheric changes to be felt at lower levels. Changes in stratospheric zonal winds can affect planetary wave propagation extending down into the troposphere, and hence the phase of the Arctic/North Atlantic oscillations. Changes in stratospheric temperatures can also affect temperatures in the upper troposphere, with a corresponding influence on tropospheric eddy energy generation and Hadley Cell intensity. Stratospheric radiative perturbations in general have a smaller impact on surface temperature than those of well-mixed or direct surface forcing due to the cloud cover response. The magnitude of the tropospheric response is generally on the order of 0–10% of control run values, while some local/extreme effects can be higher''. Thus, various possibilities need to be taken into account.

For short-term time scales (hours to days), effects like those reported by Svensmark and Friis-Christensen (1997) relating variation of cosmic ray flux and global cloud coverage, are certainly detectable, but on long-term time scale, effects become obscure. On very long-term time scale, some relationships seem to be partly valid (Eddy, 1976; Lean and Rind, 1999). A major complication is because of effects of nonsolar natural phenomena like greenhouse effects, El Niños, volcano activity, etc., which are often overwhelmingly large. Accurate measurements will probably establish solar effects beyond doubt, but the recent global temperature increases indicate that the effects of other nonsolar sources are on the increase and detecting solar effects will be increasingly more difficult.

9. Conclusions

The Sun emits a variety of radiations and corpuscular material, much more so near the maximum of an 11-year cycle. Some solar effects are felt on Earth by the direct impinging of solar radiation (visible as well as UV, EUV), while others are conveyed via the solar wind. Effects of solar variability are seen very strongly in the upper atmosphere (mainly thermospheric temperatures) but are reduced at lower altitudes. For long-term changes in terrestrial climate, the consensus seems to be that solar forcing might have contributed about half of the observed 0.55 K surface warming since 1860, and one third of the warming since 1970, the rest of the warming coming from greenhouse effects (increased CO_2, etc.), with temporary short-lived effects from volcanic eruptions, El Niños, etc. Regarding the relationship between solar variability and climate on time-scales ranging from days to centuries and millennia, McCormack and North (2004) summarize the present situation as follows:

(a) There is evidence of climatic forcings on centennial and millennial scales from ^{14}C fossil records and ice core samples (Muscheler et al., 2003).
(b) Solar forcing did contribute to the observed climate variability during the first half of the 20th century, but the exact origins of the observed climate variability related to solar forcing remain unclear. Though the largest percentage changes in solar irradiance occur at shorter wavelengths, the energy at these wavelengths represents only a small fraction of the Sun's total output and is deposited mainly in the upper stratosphere, with no direct impact on the troposphere and surface.
(c) Stratospheric responses to solar ultraviolet variations have now been observed on both the solar rotation and the solar cycle time scales. Although the observed responses are qualitatively consistent with theoretical expectations, there are important quantitative differences.
(d) For the troposphere, effects through energetic solar proton events (SPE's) and through solar modulated fluxes of galactic cosmic rays (GCR's) affecting cloud microphysical processes are possible and are under investigation.

However, it happens that the present climate models are not yet good enough for a full understanding of the situation. Much depends upon boundary conditions, and only a good first try is presently made. When all is said and done, the Sun–climate is a complicated system and will need a lot of dedicated work and patience to unravel it. This is a challenge worth taking by the present and future generations, and it is already being accepted.

Acknowledgement

This work was partially supported by Fundação Nacional de Desenvolvimento Cientifico e Tecnólogico (FNDCT), Brazil, under contract FINEP-537/CT.

References

Badalyan, O.G., Obridko, V.N., Rybak, J., Sykora, J., N–S asymmetry of solar activity and quasi-biennial oscillations, in: Wilson, A. (Ed.), Proceedings of ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 63–66, 2003.
Bahcall, J.N. Neutrinos from the sun. Sci. Am. 221 (1), 28–37, 1969.
Baker, D.N. Substorm in the Earth's magnetosphere, in: Epstein, R., Feldman, W. (Eds.), Magnetospheric Phenomena in Astrophysics. American Institute of Physics, New York, pp. 184–207, 1986.
Bartels, J. Terrestrial magnetic activity and its relations to solar phenomena. Terr. Mag. Atmos. Elect. 37, 1–52, 1932.
Belcher, J.W., Davis, L. Large amplitude Alfven waves in the interplanetary medium, 2. J. Geophys. Res. 76, 3534–3563, 1971.
Biermann, L.F. Kometenschweife und solar korpuskularstrahlung. Zeitschrift fur Astrophysik 29, 274–286, 1951.
Bochnicek, J., Hejda, P., Bucha, V., Pýcha, J. Possible geomagnetic activity effects on weather. Ann. Geophys. 17, 925–932, 1999.
Boteler, D.H., Tapping, K.F., Tracing space weather disturbances from the Sun through to their effects on the ground, Paper presented at the 35th COSPAR meeting, Paris, 2004.

Bridge, H.S., Dilworth, C., Lazarus, J., Lyon, E.F., Rossi, B., Scherb, F. Direct observations of the interplanetary plasma. J. Phys. Soc. Jpn. 11 (Suppl. A-II), 553–559, 1962.

Bucha, V., Bucha Jr., V. Geomagnetic forcing of changes in climate and in the atmospheric circulation. J. Atmos. Solar-Terr. Phys. 60, 145–169, 1998.

Bumba, V. Cyclic changes of the solar global and local magnetic field patterns, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, It Solar Variability as an Input to the Earth's Environment. ESTEC, Noordwijk, The Netherlands, pp. 23–28, 2003, September.

Burlaga, L.F., Skoug, R.M., Smith, C.W., Webb, D.F., Zurbuchen, T.H., Reinard, A. Fast ejecta during the ascending phase of solar cycle23: ACE observations, 1998–1999. J. Geophys. Res. 106, 20957–20977, 2001.

Carrington, R.C. On the distribution of the solar spots in latitude since the beginning of the year1854. Mon. Not. Roy. Astron. Soc. 19, 1–3, 1858.

Carrington, R.C. On certain phenomena in the motions of solar spots. Mon. Not. Roy. Astron. Soc. 19, 81–84, 1859a.

Carrington, R.C. Description of a singular appearance seen in the sun on september 1, 1859. Mon. Not. Roy. Astron. Soc. 20, 13–15, 1859.

Chamberlain, J.W. Interplanetary gas. II Expansion of a model solar corona. Astrophys. J. 131, 47–56, 1960.

Chapman, S. Notes on the solar corona and the terrestrial atmosphere. Smithsonian Contrib. Astrophys. 2 (1), 1–11, 1957.

Chapman, S. Interplanetary space and the Earth's outermost atmosphere. Proc. Roy. Soc. A253, 462–481, 1959.

Clark, W.E. The Aryabhattiya of ARYABHATTA (Aarya-Bhatt), an Ancient Indian Work on Mathematics and Astronomy. The University of Chicago Press, Chicago, Illinois, 1930.

Clemesha, B.R., Batista, P.P., Simonich, D.M. Long-term and solar cycle changes in the atmospheric sodium layer. J. Atmos. Solar-Terr. Phys. 59, 1673–1678, 1997.

Clemesha, B., Takahashi, H., Simonich, D.M., Gobbi, D., Batista, P.P. Experimental evidence for solar cycle and long-term change in the low-latitude MLT region. J. Atmos. Solar-Terr. Phys. 67, 191–196, 2005.

Dal Lago, A., Vieira, L.E., Echer, E., Gonzalez, W.E., Clua de Gonzalez, A.L., Guarnieri, F.L., Santos, J., Schwenn, R., Schuch, N.J., Forecasting interplanetary ejecta arrival at 1 AU, Paper presented at the 35th COSPAR meeting, Paris, 2004.

Duhau, S., Global Earth surface temperature change induced by mean Sun dynamo magnetic field variations, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 317–322, 2003.

Dungey, J.W. Interplanetary magnetic field and the auroral zones. Phys. Rev. Lett. 6, 47–48, 1961.

Eddy, J. The Maunder minimum. Science 192, 1189–1202, 1976.

Farrugia, C.J., Popecki, M., Möbius, E., et al. Wind and ACE observations during the great flow of 1–4 May 1998: relation to solar activity and implications for the magnetosphere. J. Geophys. Res. 107 (A9), 1240, 2002, SSH 3, 1-21.

Feldstein, Y., Tsurutani, B., Prigancova, A., Gonzalez, W., Levitin, A., Kozyra, J., Alperovich, L., Mall, U., Gromova, L., Dremukhina, L., The magnetospheric response to a two-stream solar wind interval during solar maximum: a self-consistent magnetospheric model, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 553–557, 2003.

Friedman, H., Rocket astronomy – an overview, in: Hanle, P.A., Del, V. (Eds.), Space science comes of age: perspectives in the history of the space sciences, in Smithsonian Institution, Chamberlain, pp. 31–44, Washington, DC, 1981.

Georgieva, K., Kirov, B., Javaraiah, J., Solar asymmetry and Sun–Earth connections, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 323–328, 2003.

Gold, T. Plasma and magnetic fields in the solar system. J. Geophys. Res. 64, 1665–1674, 1959.

Gonzalez, W.D., Dal Lago, A., Clua de Gonzalez, A.L., Vieira, L.E.A., Tsurutani, B.T. Prediction of peak-Dst from halo CME/magnetic cloud-speed observations. J. Atmos. Solar-Terr. Phys. 66, 161–165, 2004.

Gopalswamy, N., Lara, A., Yashiro, S., Nunes, S., Howard, R.A., Coronal mass ejection activity during solar cycle 23, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 403–414, 2003.

Gringauz, K.I., Bezrukikh, V.V., Ozerov, V.D., Rybchinskii, R.E. A study of the interplanetary ionized gas, high-energy electrons, and corpuscular radiation from the Sun by means of the three-electrode trap for charged particles on the second soviet cosmic rocket. Sov. Phys. Doklady 5, 361–364, 1960.

Hameed, S., Atmospheric Centers of Action as Bridges Between Solar Activity Variations and Regional Climate Change, December 2003 SORCE Sonoma Science Meeting Final Program, Sonoma, California, December 4–6, 2003.

Hood, L.L. Effects of solar UV variability on the stratosphere, in: Pap, J., Fox, P., Frohlich, C., Hudson, H., Kuhn, J., McCormack, J., North, G., Sprigg, W., Wu, S.T. (Eds.), Solar Variability and Its Effect on the Earth's Atmospheric and Climate System, AGU Monograph Series. American Geophysical Union, Washington, DC, pp. 283–304, 2004.

Hufbauer, K. Exploring the Sun: Solar Science Since Galileo. The John Hopkins University Press, Baltimore, MD, USA, 1991.

Hundhausen, A.J., Coronal Expansion and Solar Wind, Springer-Verlag, Berlin-Heidelberg, p. 238, 1972.

Jacobi, Ch. On the solar cycle dependence of winds and planetary waves as seen from midlatitude Dl LF mesopause region wind measurements. Ann. Geophys. 16, 1534–1543, 1998.

Kane, R.P. Global evolution of F2 region storms. J. Atmos. Terr. Phys. 35, 1953–1966, 1973.

Kane, R.P. Geomagnetic field variations. Space Sci. Rev. 18, 413–540, 1976.

Kane, R.P. Sun–Weather/Climate Relationship: An Update Scientific Note ISRO-SN-11-99. Indian Space Research Organization, Bangalore, India, 1999.

Kane, R.P. Dissimilarity in the evolution of solar euv and solar radio emission (2800 MHz) during 1999–2002. J. Geophys. Res. 108 (12), 1455, 2003, SSH 9, 1–4.

Kay, G.R. Hindu Astronomy, Ancient Science of the Hindus. Cosmo Publications, New Delhi, India, 1981.

Kiepenheuer, K.O. Solar activity, in: Kuiper, G.P. (Ed.), The Sun. The University of Chicago Press, Chicago, pp. 322–465, 1953.

Kirchhoff, G., Sitzungsber Akad. Wiss. Berlin, p. 783, 1859.

Kosovichev, A.G., What helioseismology teaches us about the Sun, in: Wilson, A., (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 795–806, 2003.

Krivolutsky, A., Kuminov, A., Vyushkova, T. Ionization of the atmosphere caused by solar protons and its influence on ozonosphere of the Earth during 1994–2003. Journal of Atmospheric and Solar-Terrestrial Physics 67, 105–117, 2005.

Labitzke, K. The global signal of the11-year sunspot cycle in the stratosphere: differences between solar maxima and minima. Met. Zeitschr. 10, 901–908, 2001.
Labitzke, K., van Loon, H Association between the 11-year solar cycle, the QBO and the atmosphere: a survey of recent work, in: Pecker, J.C., Runcorn, S.K. (Eds.), The Earth's Climate and Variability of the Sun over Recent Millenia. Royal Society, London, 1990.
Labitzke, K., vanLoon, H. The signal of the 11-year sunspot cycle in the upper troposphere–lower stratosphere. Space Sci. Rev. 80, 393–410, 1997.
Landscheidt, T., Solar forcing of El Niño and La Niña, in: Proceedings of the 1st Solar & Space Weather Euroconference, 'The Solar Cycle and Terrestrial Climate', Santa Cruz de Tenerife, Tenerife, Spain, 25–29 September, 2000, (ESA SP-463, December, 2000).
Lastovicka, J. The response of the lower ionosphere, stratospheric ozone and the vorticity area index to geomagnetic storms. Geomag. Aeron. 30, 380–383, 1991.
Lawrence, J.K., Cadavid, A.C., Ruzmaikin, A. The response of atmospheric circulation to weak solar forcing. J. Geophys. Res. 105, 24839–24848, 2000.
Lean, J., Rind, D. Evaluating Sun–climate relationships since the little ice age. J. Atmos. Solar-Terr. Phys. 61, 25–36, 1999.
Maricic, D., Vrsnak, B., Stanger, A.L., Rosa, D., Hrzina, D., Initiation and development of two coronal mass ejections, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 441–446, 2003.
McCormack, J.P., North, G.R. Section 3, in: Pap, J., Fox, P., Frohlich, C., Hudson, H., Kuhn, J. (Eds.), Solar Variability and Climate, Solar Variability and Its Effects on Climate, AGU Geophysical Monograph, vol. 141. American Geophysical Union, Washington, DC, pp. 219–220, 2004.
Muscheler, R., Beer, J., Kromer, B., Long-term climate variations and solar effects, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 305–315, 2003.
Ness, N.F., Wilcox, J.M. Sector structure of the quiet interplanetary magnetic field. Science 148, 1592–1594, 1965.
Neugebauer, M.M., Snyder, C.W. Solar plasma experiment. Science 138, 1095–1096, 1962.
Parker, E.N. Dynamical instability in an anisotropic ionized gas of low density. Phys. Rev. 109, 1874–1876, 1958.
Parker, E.N. Extension of the solar corona into interplanetary space. J. Geophys. Res. 64, 1675–1681, 1959.
Pawsey, J.L. Observations of million degree thermal radiation from the Sun at a wavelength of 1.5 meters. Nature 158, 633–634, 1946.
Piddington, J.H., Cosmic Electrodynamics, John Wiley and Sons Inc., New York. p. 87, 1969.
Pittock, A.B. A critical look at long-term Sun–weather relationships. Rev. Geophys. 16, 400–420, 1978.
Prikryl, P., Muldrew, D.B., Sofko, G.J., High-speed solar wind, auroral electrojets and atmospheric gravity waves: a link to the Earth's atmosphere, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 371–376, 2003.
Ramaswamy, V., Chanin, M.L., Angell, J., et al. Stratospheric temperature trends: observations and model simulations. Rev. Geophys. 39, 71–122, 2001.
Reddy, R.S., Some aspects of recent studies in solar-terrestrial relations, in: Abstract 6.8.4 IX, presented at the ISCS 2001 Solar Variability, Climate and Space Weather Conference, Longmont, Colorado June 13–16, 2001.
Reddy, R.S., Karim, R., Effects of 11-year solar cycle and quasi-biennial oscillation (QBO) on the energetics in the equatorial lower stratosphere and large-scale tropical circulations, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 381–383, 2003.
Rind, D., Mechanisms of Solar Influence on the Troposphere via the Stratosphere, December 2003 SORCE Sonoma Science Meeting Final Program, Sonoma, California, December 4–6, 2003.
Roble, R.G.. in: Solar Drivers of Interplanetary and Terrestrial DisturbancesASP Conference Series, vol. 95. Astron. Soc. Pac., pp. 609–618, 1996.
Sabine, E. On periodical laws discoverable in the mean effects of the larger magnetic disturbances- No. 2. Phil. Trans. 142, 103–124, 1852.
Sangalli, L., Wade, G.A., Noel, J.M., Modeling the thermospheric response to solar activity using the NORAD satellite catalogue, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 385–388, 2003.
Schatten, K.H., Wilcox, J.M., Ness, N.F. A model of interplanetary and coronal magnetic fields. Sol. Phys. 6, 442–455, 1969.
Scheer, J., Reisin, E.R., Mandrini, C.H. Solar activity signatures in mesopause region temperatures and atomic oxygen related airglow brightness at El Leoncito, Argentina. J. Atmos. Solar-Terr. Phys. 67, 145–154, 2005.
Schwabe, A.N. Sounen–Beobachtungen in Jahre 1843. Astron. Nachr. 21, 233–246, 1843.
Sen, S.N., Shukla, K.S. History of Astronomy in India. Indian National Science Academy, New Delhi, 1985.
Simnett, G.M., A new concept for solar flares, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 613–618, 2003.
Snyder, C.W., Neugebauer, M.M., Rao, U.R. The solar wind velocity and its correlation with cosmic-ray variations and with solar and geomagnetic activity. J. Geophys. Res. 68, 6361–6370, 1963.
Svensmark, H., Friis-Christensen, E. Variation of cosmic ray flux and global cloud coverage – a missing link in solar climate relationships. J. Atmos. Solar-Terr. Phys. 59, 1225–1232, 1997.
Stott, P.A., Tett, S.F.B., Jones, G.S., Alien, M.R., Mitchell, J.F.B., Jenkins, G.J. External control of 20th century temperature by natural and anthropogenic forcings. Science 290, 2133–2137, 2000.
Strestik, J., Possible correlation between solar and volcanic activity in a long-term scale, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 393–396, 2003.
Tinsley, B.A. Influence of the solar wind on the global electric circuit and inferred effects on cloud microphysics, temperature and dynamics of the troposphere. Space Sci. Rev. 94, 231–258, 2000.
Tobiska, W.K., Woods, T., Eparvier, F., Viereck, R., Floyd, L., Bouwer, D., Rottmann, G., White, O.R. The SOLRAD2000 empirical solar irradiance model and forecast tool. J. Atmos. Solar-Terr. Phys. 62, 1233–1250, 2000.
Tousey, R.. in: Rycroft, M.J., Runcom, S.K. (Eds.), The Solar Corona. Springer-Verlag, New York, p. 173, 1973.
Tousey, R. Solar spectroscopy from Roland to SOT. Vistas Astron. 29, 175–199, 1986.
Viereck, R., McMullin, D., Fuller-Rowell, T., Solar EUV flares and their effect on the terrestrial atmosphere, Geophys. Res. Abstracts, vol. 5, 07136, European Geophysical Society, 2003.
Wilcox, J.M. The interplanetary magnetic field. Solar origin and terrestrial effects. Space Sci.Rev. 8, 258–328, 1986.

Wolf, J.R. Erinnerungen an heinrich samuel schwabe. Vierteljahrschrift der Naturfor schenden Gesellschaft zu Zurich 21, 129–145, 1876.
Youssef, M., El-Nawawy, M.S., Youssef, M.S., The Earth's magnetosphere during the solar wind disappearance, in: Wilson, A. (Ed.), Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, Tatranská Lomnica, Slovakia, ESA SP-535, ESTEC, Noordwijk, The Netherlands, September, pp. 761–774, 2003.
Zirin, H. Astrophysics of the Sun. Cambridge University Press, Cambridge, 1988.