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# A Historical Review of the Geomagnetic Storm-Producing Plasma Flows from the Sun

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**Abstract** The concept of geomagnetic storm-producing solar plasma flows has evolved and advanced considerably over the last 100 years or so. This particular field of study began in an effort to understand geomagnetic disturbances and the aurora. The purpose of this paper is try to follow the ways in which early concepts evolved to later ones, not to review each concept in detail. It is fascinating to see a step-by-step buildup of these concepts, from the earliest idea of flow of solar electrons to coronal mass ejections (CMEs). The time line, though tentative, of the studies of geomagnetic storm-producing plasma flows is presented. The author hopes that this paper will serve young researchers in particular to consider how they plan to advance further this scientific field. There is still much uncertainty about geomagnetic storm-producing solar plasma flows. Some of the major questions are listed from the point of view of a geophysicist in the summary sections by grouping them in terms of the quiet-time solar wind, solar streams from corona holes and CMEs associated with solar flares.

**Keywords** Solar plasma · CMEs · Geomagnetic Storm · History

## 1 Solar Electron Theories

### 1.1 Carrington's First Observation of a Solar Flare

Carrington's job at the Greenwich Observatory was to observe sunspots every day by sketching them. By Carrington's time, photography had become available, and although Carrington's colleagues suggested that he might use it, he refused to do so. On September 1, 1845, he witnessed bright spots among sunspots at 11:15 UT. Not trusting his eyes, he called some of his colleagues to confirm the spots. He found also that a magnetometer at the observatory showed a small magnetic change at the same time. (We now know that this change was produced by an increase of ultraviolet light, which augments the solar quiet day daily variation

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by ionizing the ionosphere. This change is called Sqa; see Nagata (1952) and Akasofu and Chapman (1972, p. 565)). On the next day, the Earth experienced a great auroral display at a large number of locations, including Hawaii. The Earth also experienced intense magnetic disturbances. The Kew magnetic record on that day is reproduced in Geomagnetism, vol. I, p. 333, Chapman and Bartels (1940). Carrington (1860) concluded his report by carefully stating "One swallow does not make a summer."

### 1.2 Lord Kelvin's "A Fifty Years' Outstanding Difficulty"

Carrington's modest statement got much attention from British physicists in those days. On September 30, 1892, during the Anniversary Meeting of the Royal Society of London, England, Kelvin (1892) summarized his study and others. He attempted to explain the geomagnetic storm field variations as a direct result of changes of the magnetic field of the Sun, located about 200 solar radii away. He estimated that the expected change of the solar dipole moment was too large to be reasonable. He concluded:

> Guided by Maxwell's 'electro-magnetic theory of light', and the undulatory theory of propagation of magnetic force which it includes, we might hope to perfectly overcome a fifty years' outstanding difficulty in the way of believing the Sun to be the direct cause of magnetic storms in the Earth, though hitherto every effort in this direction has been disappointing. It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sunspots is unreal, and that the seeming agreement between the periods has been mere coincidence.

Obviously, he was unaware of solar plasma flows, which can communicate solar activities to the Earth.

### 1.3 Suggestions by J.J. Thomson and G.P. Thomson

One of the first direct suggestions between the Sun and the aurora in terms of electrons was made by J.J. Thomson and G.P. Thomson (1969), after the discovery of electrons in 1897, the following in their treatise *Conduction of Electricity through Gases* (cf. Dover, 1969, p. 349).

We may thus regard the Sun, and probably any luminous star, as a source of negatively electrified particles which stream through the solar and stellar systems. Now when electrons moving at a high speed pass through a gas they make it luminous; thus when the electrons from the Sun meet the upper regions of the Earth's atmosphere they will produce luminous effects. Arrhenius has shown that we can explain in a satisfactory manner many of the periodic variations in the Aurora Borealis if we assume that it is caused by electrons from the Sun passing through the upper regions of the Earth's atmosphere (Thomson and Thomson 1903).

Being aware of the discovery of electrons by J.J. Thomson, Birkeland (1908) stated:

> It has gradually come to be acknowledged that aurora and magnetic perturbations should be regarded as rather moderate manifestations—at present the only ones there are for us to observe—of an unknown of solar origin, and quite different from light, heat, or gravitation. It has long been supposed that this unknown aspect was in some way or other of an electrical nature.

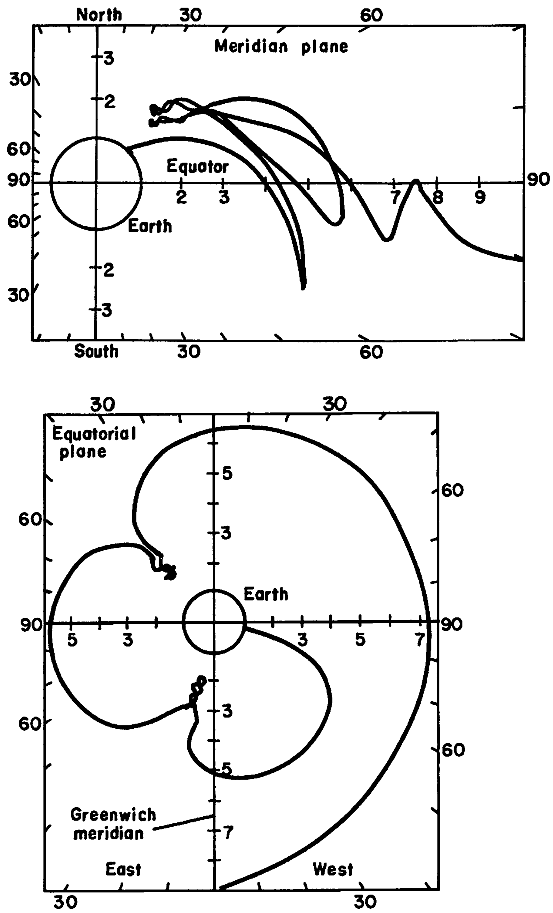



**Fig. 1** An example of the trajectories of an electron in a dipole field, computed by Stormer (1955)

## 1.4 Birkeland's Experiment and Stormer's Study

Birkeland conducted a laboratory experiment to prove his idea, in addition to his extensive observation of magnetic disturbances and the aurora. He made a large vacuum box with a magnetized sphere, called a *terrella*, and an electron gun. The terrella was coated with fluorescent paint, so that the area of electron impacts became luminous, simulating the aurora. This device is exhibited at the University of Tromso.

Stormer (1955), inspired by the terrella experiment, began his lifelong study of trajectories of electrons in a dipole field (Fig. 1).

Unfortunately, his study of motions of solitary electrons in a dipole field was found to be not applicable to the solar plasma flow from the Sun, but it became useful later in understanding trajectories of cosmic-ray particles in the vicinity of the Earth. Further, Stormer found that there is a group of trajectories confined near the Earth, not connected to infinity (the Sun). When the radiation belt surrounding the Earth was discovered by Van Allen (1959), he correctly recognized energetic particles in the belt as such particles.

## 1.5 Maunder's Confirmation of the Solar-Terrestrial Relationship

Despite a strong rejection of solar effects on geomagnetic disturbances by Kelvin, Maunder (1905) examined the 27-day recurrence tendency on the basis of magnetic records at the Greenwich Observatory and concluded:

> First: The origin of our magnetic disturbances lies in the Sun; not any body or bodies affecting both. This is clearly from the manner in which those disturbances mark out the solar rotation period.
> Second: The areas of the Sun giving rise to our magnetic disturbances are definite and restricted areas … not due to a general action or influence diffuse over the solar surface …. Such a relation can only be explained by supposing that the Earth has encountered, time after time, a definite stream, a stream which, continually supplied from one and the same area of the Sun's surface, appears to us, at our distance, to be rotating with the same speed as the area from which it rises.

> Ninth: … Though sunspots and magnetic disturbance are intimately connected, large sunspots will often be observed when no disturbances are experienced, whilst sometimes disturbances will be experienced when no spots with which they can be associated are visible.

It is truly amazing that all his statements are accurate even by today's standards. He introduced the term "stream" and identified the source area that we now identify as the coronal hole. These points will be discussed in Sect. 2.9 and other sections in terms of the development of the solar-terrestrial relationship.

With a firm confidence, he concluded his study in the following:

> That, therefore, which Lord Kelvin spoke of twelve years ago as "the fifty years' outstanding difficulty" is now rendered clear. Our magnetic disturbances have their origin in the Sun.

## 1.6 Schuster's Objection to Maunder's Paper

Repeating arguments similar to that of Kelvin, Schuster (1905) presented a strong objection to Maunder's findings and conclusions. He began his argument by stating:

> I approached the study of Maunder's paper in a somewhat doubtful spirit …. The result has convinced me that, subject to certain qualifications, Mr. Maunder has made good his contention that magnetic storms are apt to recur in periods not differing much from that of the mean rotation of the sunspot zones. This is a very important result, but in trying to fit a theory to suit new facts we must not forget that older and at least equally well established ones cannot be ignored, and those do not support the theoretical views which are brought forward by Mr. Maunder.

At the end of his paper, Schuster concluded:

> He has, no doubt, added a new fact and made an important contribution to the subject. He has given renewed interest to it and brought out urgent important of further investigation, but the mystery is left more mysterious than ever; the facts have become harder to understand and more difficult to explain.

However, later Schuster (1911) became aware of the possibility of Maunder's stream and began his paper by stating:

> Lord Kelvin, in discussing the origin of magnetic storms, came to the conclusion that they could not be due to a direct solar action on account of the enormous energy which would have to be supplied by the Sun. This verdict was generally accepted until recently, when the theory of a direct solar action has been revived in a form, which is assumed to be free from the objection raised, the magnetic action being supposed to be due to a swarm of electrified corpuscles ejected by the Sun.

For this reason, he examined the propagation of "a swarm of electrified corpuscles" but concluded:

> A swarm of electrons packed with sufficient density to cause a magnetic action becomes negligible.

And he stated further:

> We must reject that theory and can do so without a pang of regret .... The magnetic effects of such rays could not reproduce, even roughly, the characteristic features of a magnetic disturbance.

In modern terms, he was stating that the IMF field is too weak to be observed on the surface of the Earth. However, he left open the possibility that, as Birkeland suggested, something might occur if a swarm of electrons comes very close to the Earth.

## 1.7 Chapman's First Theory of Geomagnetic Storms

Chapman (1918) wanted to examine physical processes of geomagnetic disturbances studied statistically by Maunder. Chapman's paper titled "An outline of a theory of magnetic storms" consists of two parts. The first is a detailed analysis of geomagnetic storm fields at different latitudes (three groups) for different intensities (great, active, moderate); this work is reproduced in Chap. 9 of *Geomagnetism* by Chapman and Bartels (1940).

Before explaining Chapman's first theory, it is necessary to describe the *solar quiet day daily variation*, denoted by Sq. The Earth experiences a fairly regular magnetic variation every day, even on quiet days. This phenomenon is caused by the tidal motion of the upper atmosphere, the ionosphere, which is electrically conductive, across the Earth's magnetic field.

The tidal flow pattern is fixed with respect to the Sun, so that the induced current pattern and the resulting magnetic variation observed on the ground are also fixed with respect to the Sun. Thus the Earth rotates under the fixed pattern of the ionospheric current once a day. Chapman's first major paper in geomagnetism, his debut paper, was the theory of Sq. In later years, Chapman tended to interpret geomagnetic storm fields under this concept, namely, the storm current system is fixed with respect to the Sun for at least 24 hours, and the Earth rotates under it once a day.

In the first of his paper, Chapman analyzed the horizontal component of the geomagnetic field, denoted by D, using in essence the Fourier analysis:

$$\mathrm{D}(\theta, \lambda, t) = \mathrm{Dst}(\theta, t) + \mathrm{SD}\sin(\theta, \lambda, t) + \mathrm{Di},$$

where $\theta$, $\lambda$, and $t$ denote latitude, longitude, and time, respectively. Thus the term Dst component is constant in terms of $\lambda$, namely, symmetric with respect to the geomagnetic axis.

Later Dst has been considered to be the field of the ring current which causes the main phase of geomagnetic storms (Sect. 8, Fig. 36). The harmonic term is denoted by SD. Chapman gave the equivalent current system for both Dst and SD on a spherical shell concentric to the Earth. In addition to the above two terms, Chapman denoted "irregular changes" by Di, which is now identified as the field of substorms which are the element of geomagnetic storm.

Chapman's analysis of geomagnetic disturbances (Sect. 1.6) indicated that geomagnetic storms consist of three phases, after the sudden commencement (see Sect. 2.2), the initial phase, the main phase, and the recovery phase. (However, the present author is not sure if Chapman was the first to use these terms.)

In the second part of his paper, Chapman assumed a "corpuscular stream" of either positive or negative sign. Upon entering the upper atmosphere, it produced upper atmospheric motions (by electrostatic repulsive force) and the resulting induced currents caused geomagnetic disturbances. Chapman mentioned many times that his first theory was "phony," although he was confident about the validity of his analysis. A package he kept for a long time wrapped in waterproof paper contained numerical tables that he used in the paper.

### 1.8 Lindemann's Criticism of Chapman's First Theory of Geomagnetic Storms

Chapman's paper was criticized almost immediately by Lindemann (1919). Lindemann opened his argument by stating:

> There seems to be no doubt that terrestrial magnetic storms are connected in some way with solar disturbances. It would seem, however, that all the theories so far put forward break down when the quantities are considered. The object of this note is to put forward a tentative suggestion which does not appear to lead to any inconsistent result quantitatively even though, like the earlier theories, it involves some assumptions. The best way to approach the subject is probably by criticizing the theory now probably most generally accepted, which has been most elaborately worked out by Dr. Chapman.

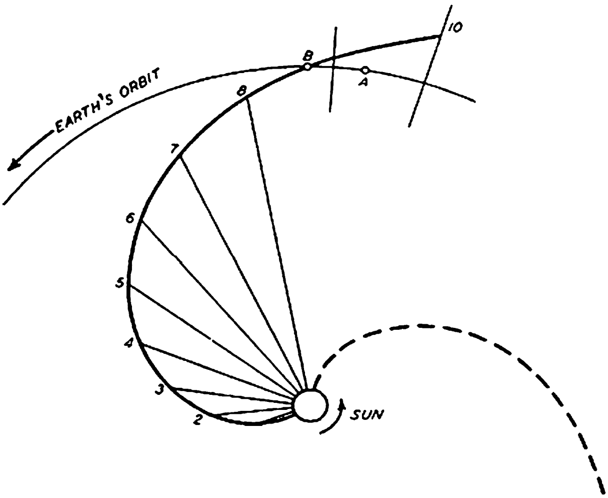
Lindemann estimated the degree of ionization of the solar stream of the initial temperature $T = 6000^\circ$ K and concluded that "ionization would be almost complete" along its way to the Earth. (The present author could not follow Lindemann's derivation of this particular point in this paper. Chapman mentioned that Lindemann derived an equation similar to the Saha equation.) Chapman took this suggestion seriously and began his study of the interaction of a fully ionized gas, which we now call 'plasma,' with the Earth's dipole field. This theory is described in Sect. 2.2. The degree of ionization of solar streams will be discussed in Sect. 5.3.

## 2 The Solar Plasma Flows

### 2.1 Chapman's View of the Solar Stream

Chapman (1929) was the first to consider the geometry of Maunder's stream. It is basically the same spiral feature as what we envisage today (Fig. 2). Although the plasma flow advances in the radial direction from the Sun, the front of the flow has a spiral structure. A similar figure is shown in Chapman and Bartels (1940).

**Fig. 2** Chapman's view of the solar stream (Chapman 1929)




## 2.2 Chapman-Ferraro Theory

Chapman was the first to apply Lindemann's suggestion that the solar stream is a plasma. With his first graduate student, V.C.A. Ferraro, he formulated the interaction between an advancing plasma and a dipole field (Chapman and Ferraro 1931). They derived an equation similar to the Debye formulation and made sure that the dimension they dealt with was much larger than the Debye length. They showed that the advance of the plasma is stopped by the induced current ($\boldsymbol{J} \times \boldsymbol{B}$ force) at the front of the plasma. This current $\boldsymbol{J}$ is called the Chapman-Ferraro current (Fig. 3a). As the magnetic field produced by the Chapman-Ferraro current is added to the dipole field, the result is as if the dipole field is 'compressed,' causing an increase of the Earth's field (Fig. 3b). They proposed that the so-called 'sudden commencement' of the geomagnetic field, a step function-like increase of the field (Fig. 3c), is caused by the induced current. Their theory was confirmed by a satellite observation (Cahill and Amazeen 1963).

In essence, the Chapman-Ferraro theory indicates that the Earth's dipole field is confined in a comet-shaped cavity, which we now call the 'magnetosphere,' a term coined by Gold (1959). This was the first theory of the formation of the magnetosphere. Since interplanetary space was considered to be a vacuum at that time, it was thought that the magnetosphere was formed intermittently when the Earth was engulfed by the solar streams. The discovery of the solar wind indicates that the magnetosphere is a permanent feature of the Earth. Later, it was found that a shock wave is formed at the front of the magnetosphere (Ness et al. 1964) (Fig. 3d).

## 2.3 Biermann's Study of Comet Tails

Comet tails are directed approximately in the anti-sunward direction. It had long been thought that solar radiation pressure was responsible for this trend. Biermann (1951, 1953) examined the magnitude of acceleration of ionized components in the tail, such as $CO^+$ and $N_2^+$, and found that it is $10^2$–$10^3$ times solar gravity. He concluded:

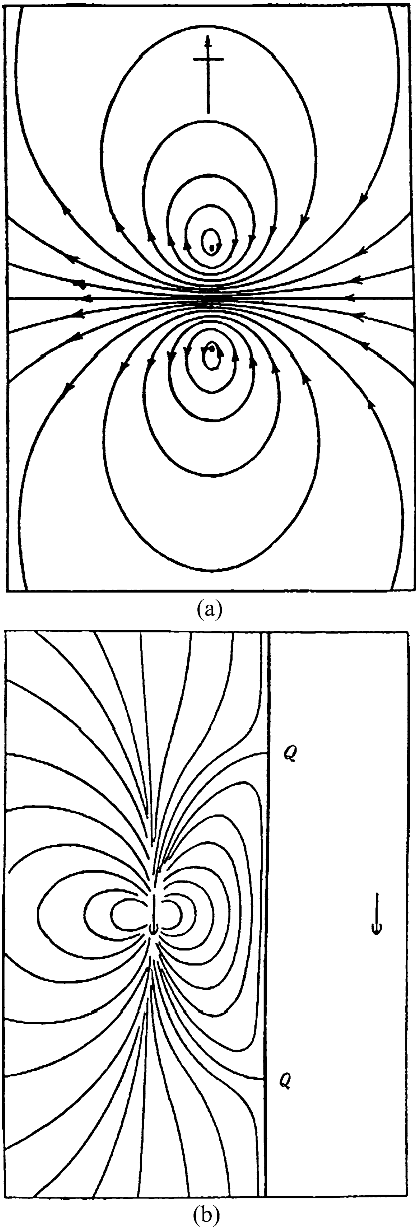
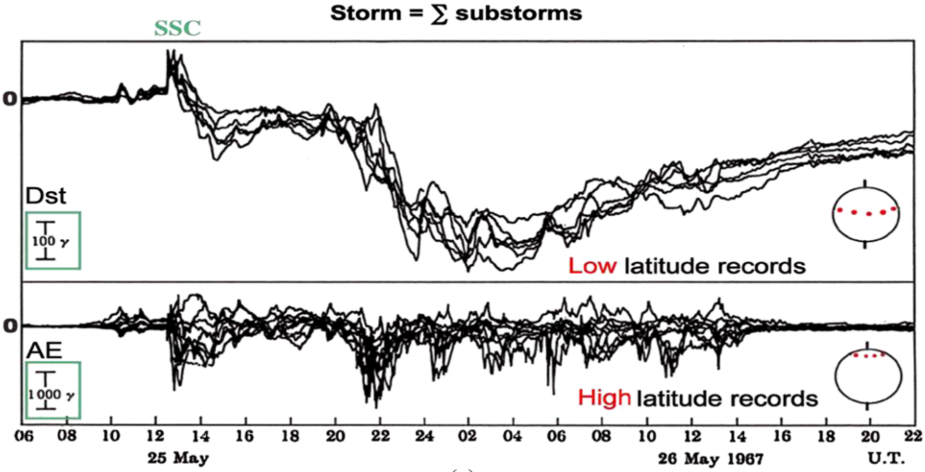


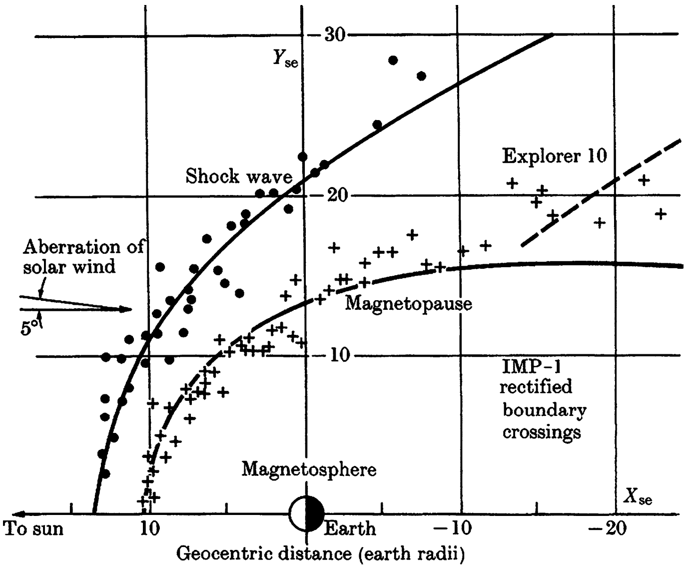

**Fig. 3** (**a**) The induced current at the front of the advancing plasma flow on the front of the magnetosphere; this current is now called the Chapman-Ferraro current (Chapman and Ferraro 1931). (**b**) The magnetic field induced by the Chapman-Ferraro current changes the dipole field as if it compresses the dipole field (Chapman and Ferraro 1931). (**c**) A typical geomagnetic storm. The *upper part* shows a combined record from low latitude stations (the Dst index is obtained by averaging the changes) and the lower part from high latitude stations (the AE index is defined as the distance between the upper and lower traces). Note the difference of scale. The sudden commencement is clearly shown. A negative change in the Dst indicates the occurrence of a southward-oriented field. (**d**) The cross-section of the magnetosphere on the equatorial plane and the shock structure at the front of the magnetosphere (Ness et al. 1964)

> It seems quite impossible to account for acceleration of this magnitude by the action of the pressure of Sun light .... It is thus found that the acceleration of the $CO^+$ and $N_2^+$ formations observed in the tails are easily explained in terms of the friction between the solar and the comet ions.

Since the tails of comets are always directed approximately to the anti-solar direction everywhere in interplanetary space, his study suggested that the Sun is blowing out continuously its atmosphere into the entire interplanetary space.




(c)




(d)

**Fig. 3** (*Continued*)

## 2.4 Chapman's Study of the Solar Corona

In the late 1950s, Chapman was interested in the zodiacal light, the solar corona, and the high temperature of the upper ionosphere. He was trying to explain the high temperature of the upper ionosphere by the heat conduction from the solar corona. Thus he considered that the solar corona extended beyond the distance of the Earth and considered a static model of the solar corona. However, his paper was rejected by one journal, but it was published in another journal (Chapman 1957).

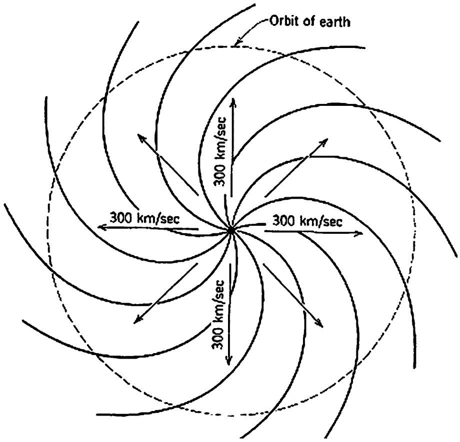



**Fig. 4** Parker's spiral pattern of the interplanetary magnetic field (Parker 1958)

## 2.5 Parker's Theory of the Solar Wind

Parker (1958) noticed Chapman's paper and found that Chapman's solution showed a finite pressure at infinity. In order to avoid this problem, he considered a steadily expanding solar corona, which can provide a supersonic flow inferred by Biermann (1951, 1953). He found several solutions for a thermally expanding model and chose the one in which the pressure at infinity goes to zero (the nozzle model). By suggesting such a possible solution, he coined the term 'solar wind' for the expanding corona. The first observations of the solar wind by the Mariner 2 space probe were considered to be the confirmation of Parker's theory (Neugebauer and Snyder 1962). His theory was later articulated and elaborated on by Hundhausen (1972), and many others. Parker's model required a specific temperature distribution of the corona as a function of height, but later observations did not support it. However, the popularity of Parker's theory overwhelmed such observations.

Since then, a large number of papers have been published on both the heating process of the solar corona and the generation mechanism of the solar wind (see Schwenn 2007 for an extensive review). It was once thought that shock waves generated on the photospheric granulations or that Alfven waves heat the solar corona and generate the solar wind. However, there is so far no accepted theory on both coronal heating and the origin of the solar wind. One recent idea is that a large number of magnetic funnel-like structures in the coronal hole may be responsible for accelerating coronal plasma (Tu et al. 2005). In any case, some electromagnetic processes involving $\boldsymbol{J} \times \boldsymbol{B}$ force may be needed to sufficiently accelerate the coronal gas. On the other hand, Parker inferred that the interplanetary magnetic field is brought out by the supersonic solar wind (Fig. 4). Later, the three-dimensional structure of the interplanetary magnetic field in the heliosphere was modeled by Akasofu and Covey (1981) (see Fig. 5).

## 2.6 Latitudinal Gradient of the Solar Wind Speed

By combining data from several spacecraft, McComas et al. (2003) found that the speed of the solar wind increases towards higher latitudes (Fig. 6a). Since the Earth is located between $\pm 7°$ during the course of one year ($+7°$ in September and $-7°$ in March), the Earth tends to experience higher speeds during equinoctial months. The slope of solar wind speed variations within the latitude of $\pm 7°$ is important in understanding the outstanding

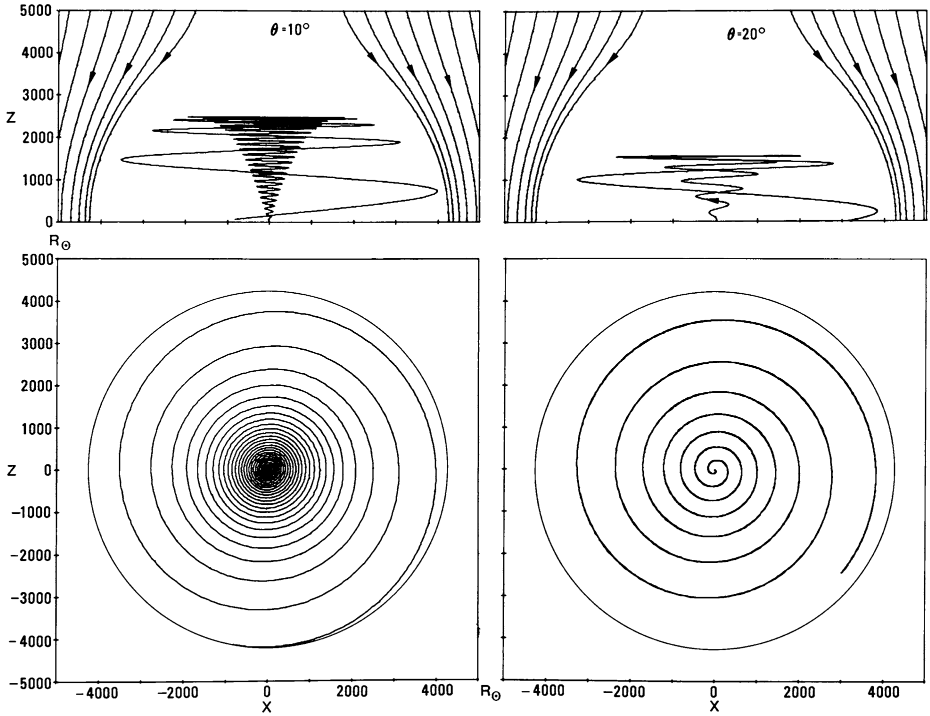



**Fig. 5** The three-dimensional magnetic field structure of in a spherical heliosphere (the northern hemisphere). The field lines from 10° and 20° from the pole are shown (Akasofu and Covey 1981)

seasonal variation of geomagnetic disturbances, namely the equinoctial maxima (Fig. 6b); this subject will be discussed further in Sect. 3.4.

## 2.7 The M-Region

Maunder's study of the 27-day recurrence tendency was succeeded by Bartels (1932). He introduced two geomagnetic indices, Kp and C9, and devised various graphical methods to display those indices. His method shows very well long term trends of geomagnetic activities. Figure 7a shows the C9 index for the declining period of three sunspot cycles. The C9 index is devised in such a way that larger geomagnetic activities are shown by larger and thicker numbers. The numbers are aligned for each solar rotation of the period of 27 days in a row. It can be seen that there were two recurrent activities for more than one year in 1974–1975. This is because there were two large coronal holes, separated by about 180° in longitude, which extended from both polar regions across the equator (see Fig. 9). This situation is later modeled in Fig. 16. The simulated geomagnetic disturbances caused by the M-region are shown in Sect. 3.6.

Bartels confirmed Maunder's ninth conclusion and noted:

> The existence of persistent active areas on the Sun's surface, called M-regions, which, in many cases, cannot be coordinated to such solar phenomena as are observable by direct astrophysical method.

Bartels called the source region of the Sun the 'M-region.' It is generally believed that 'M' signifies 'magnetically active' regions, but it has often been referred to as a 'mysterious'

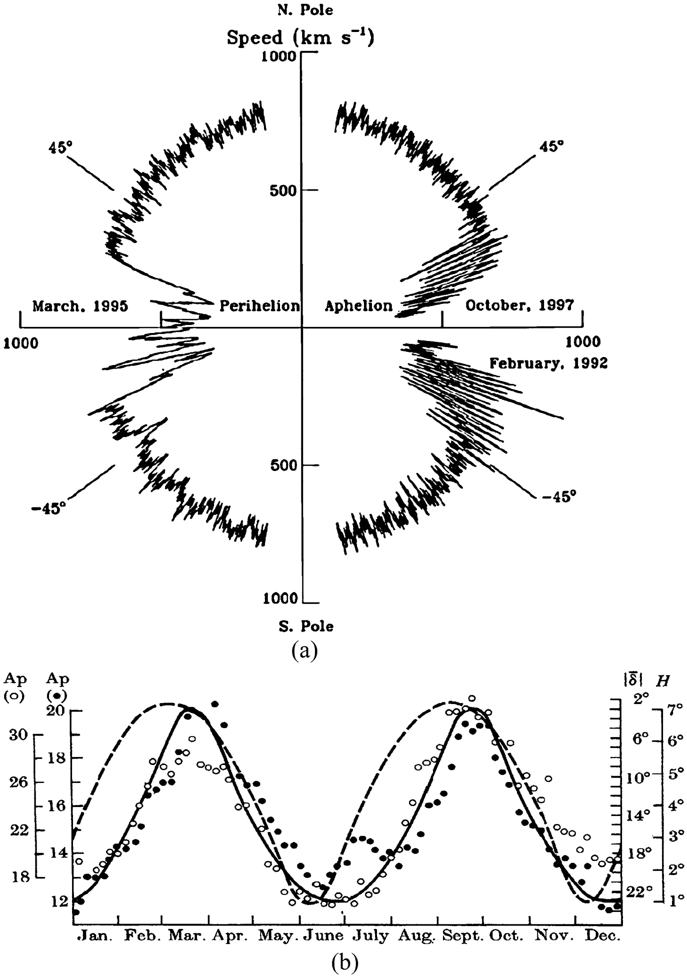



**Fig. 6** (**a**) The latitudinal dependence of the solar wind speed (McComas et al. 2003). (**b**) The seasonal variation of geomagnetic disturbances in terms of the geomagnetic index Ap. *Dots*: The average between 1932 and 1961. *Circles*: during M-region disturbances. $\delta$—the solar declination and H—the heliographic latitude (Roosen 1966, see also Akasofu and Chapman (1972, p. 549))

region, since it causes geomagnetic activities without any definite sign of solar activity. This region was later identified as a coronal hole (Sect. 2.9), in which there is no large sunspot.

Meanwhile, a new instrument for observing weak fields on the surface of the Sun was developed by Babcock (1953). Solar magnetic records were then analyzed extensively by Babcock and Babcock (1955), who found that large areas of only one outstanding polarity, positive or negative, occur on the photosphere (Fig. 7b) and that they persist for many months. Such regions are called 'UM-regions (unipolar magnetic regions).' Babcock and Babcock (1955) suggested that "it may well have been related to a prominent sequence of 27-day-recurrent the heretofore hypothetical 'M' regions of Bartels."

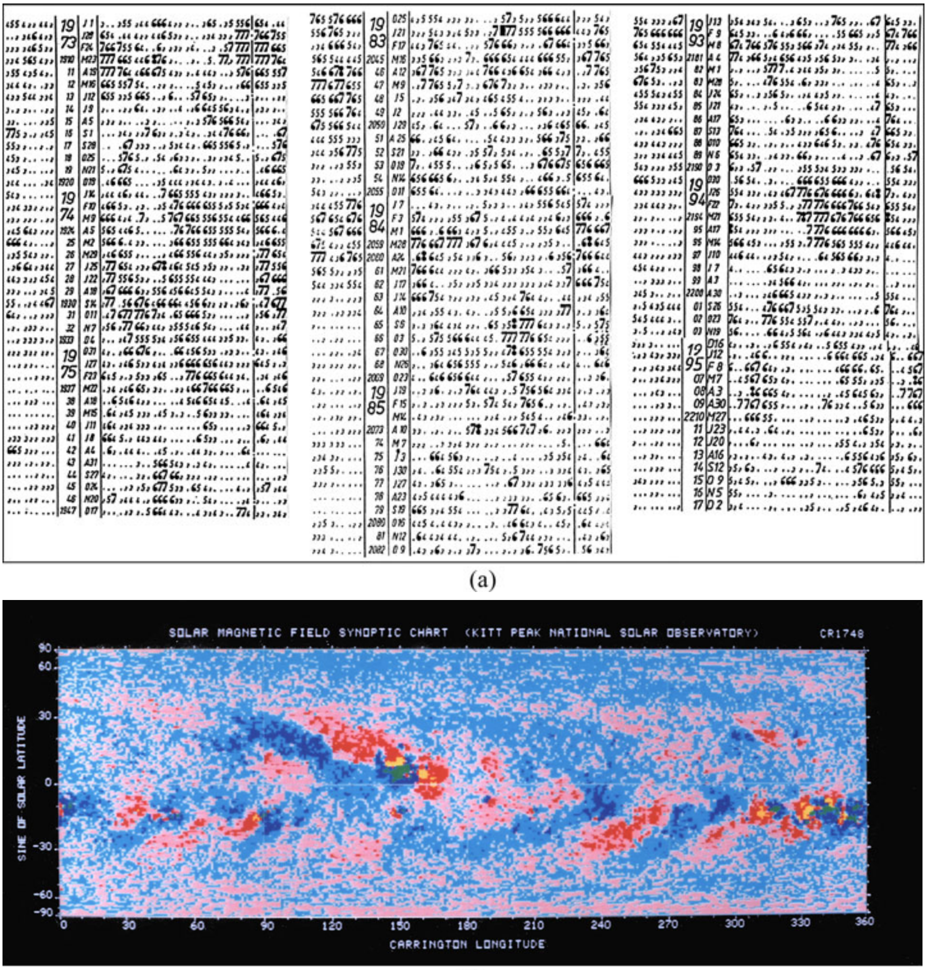



**Fig. 7** (**a**) Bartels' C9 index in 1973–1975, 1983–1985. 1993–1995 (during the declining periods of the sunspot cycles), indicating the presence of streams from the Sun. The index is shown for each solar rotation period (27 days seen from the Earth) in a row. From the *left column*, year/month/date, the solar rotation number, C9 index (Institut fur Geophysik). (**b**) The magnetic map of the Sun, showing UM-regions (*red*-positive and *blue*-negative) (Courtesy of K. Hakamada)

## 2.8 The Concept of Cone of Avoidance

The important effects of the magnetic fields on the photosphere on the solar plasma stream was inferred by Pecker and Roberts (1955) as early as 1955 on the basis of their study of the relationship between sunspots and geomagnetic disturbances. Billings and Roberts (1964) proposed the concept of 'cone of avoidance,' suggesting that a loop structure of an active region tends to suppress and deflect ejected solar 'corpuscles' in such a way as to result in not only a cone of avoidance of corpuscles above an active region, but also two beams of corpuscles at the boundary of the cone of avoidance (Fig. 8a). In fact, the sunspot number and the solar wind speed are almost anti-correlated, as shown in Fig. 8b. This is because the

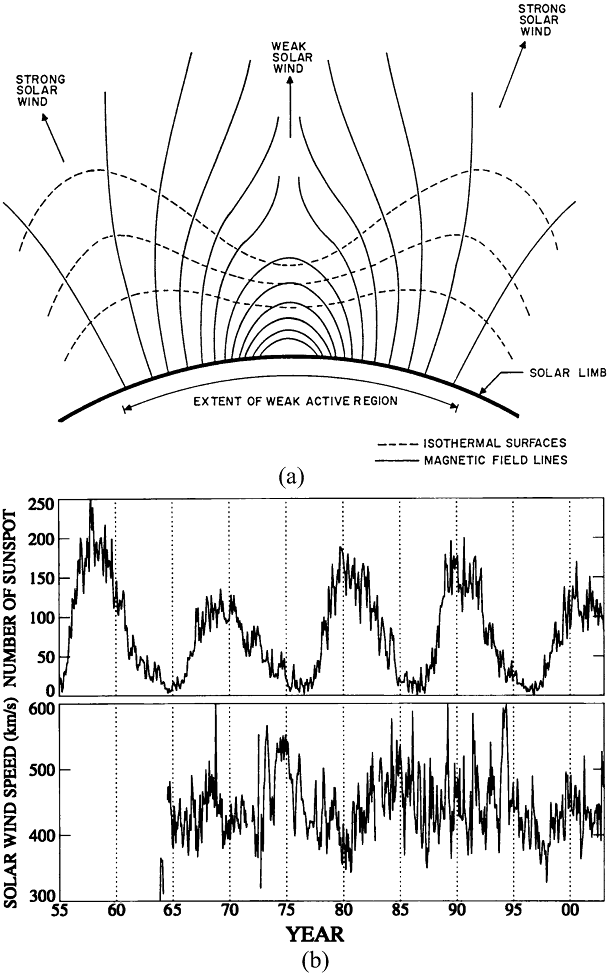



**Fig. 8** (**a**) Schematic illustration of the cone of avoidance. The loop structure tends to prevent the flow of solar plasma (Billings and Roberts 1964). (**b**) The relationship between the sunspot number and the solar wind speed. The sunspot maximum period does not coincide with the period of the highest solar wind speed

streams from large coronal holes tend to appear after the maximum epoch of the sunspot cycle, as discussed in the next section. Coronal holes tend to appear in the area without large sunspot groups.

## 2.9 Coronal Holes

Coronal holes are defined as regions of abnormally low density and temperature in the solar corona (Zirker 1977). The historical grounds leading to the discovery of the coronal holes are described by Bohlin (1977). Beginning in 1957, a large number of coronal observations suggested the presence of large-scale areas of weak brightness at both low latitude regions and the polar region. However, soft X-ray photographs of the Sun taken from the SKYLAB exhibited "visibly" coronal holes for the first time (Fig. 9).

The identification of the coronal hole as the source of high-speed streams of the solar wind was made by Krieger et al. (1973). Subsequently, the permanent polar coronal hole in each polar region, when it is extended to lower latitudes, was identified as the source of recurrent geomagnetic disturbance flow. Neupert and Pizzo (1974) concluded that:

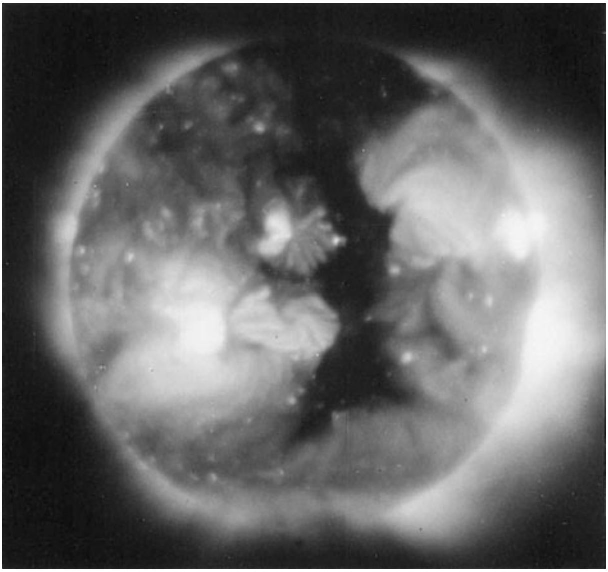


**Fig. 9** A well developed corona hole in 1974; note that the northern coronal hole extends across the equator (Courtesy of American Science & Engineering, Inc.)

> Large coronal holes, which are frequently recurrent long-lived features, appear to satisfy the requirements for 'M-regions' which were hypothesized to be responsible for recurrent geomagnetic disturbances.

As mentioned in Sect. 2.7, in 1974–1975, two large and long-lasting coronal holes extended from both the northern and southern polar regions of the Sun, located about 180° apart in longitude. Both of them extended across the magnetic equator to the other hemisphere; this feature is modeled in Sect. 3.6. Because of this extraordinary extension, these coronal holes caused intense geomagnetic storms twice in one solar rotation, 13–14 days apart. Figure 7 shows clearly two periods of geomagnetic disturbances in each solar rotation period. Small coronal holes, which occur often in low latitudes and are not connected to the polar coronal holes, do not last long and the resulting magnetic disturbances tend to be weak.

## 3 Interplanetary Magnetic Field (IMF)

### 3.1 Recognition of the Importance of the IMF

Hoyle (1949), Alfven (1950), and Dungey (1958) were the first to recognize the importance of the interplanetary field (IMF). Their idea was that the interaction of the interplanetary magnetic field and the geomagnetic field will produce neutral point(s) and that electrical discharge from the neutral point(s) to the polar regions causes the aurora. The first observation of the IMF was made by Sonett et al. (1960) on the basis of Pioneer 5 observation.

### 3.2 Dungey's Theory

Dungey (1961) applied what we call now the theory of magnetic reconnection for the interaction between the IMF and the geomagnetic field (Fig. 10), although his main point

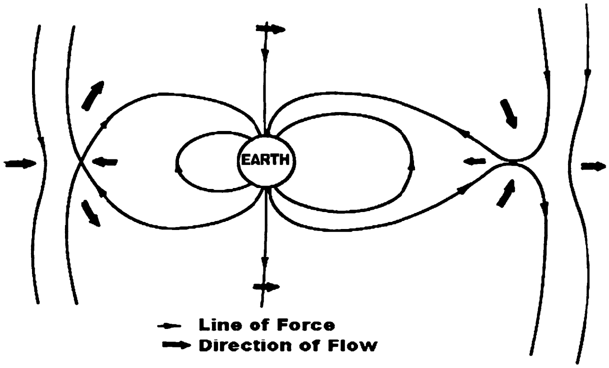



**Fig. 10** Dungey's concept of the magnetosphere (Dungey 1961)

was electrical discharge through the neutral points. Actually, Dungey combined Chapman's theory of the interaction between the solar plasma and Alfven's theory of the interplanetary magnetic field. Dungey's theory has become the foundation of magnetospheric physics. Dungey considered that auroral activities arise from the imbalance of magnetic reconnection on the dayside and night side and suggested that the night side reconnection occurs intermittently, producing auroral substorms, when the magnetic flux in the tail region exceeds some value. The question of how magnetic reconnection is related to auroral substorms is a matter of intense debate in recent years.

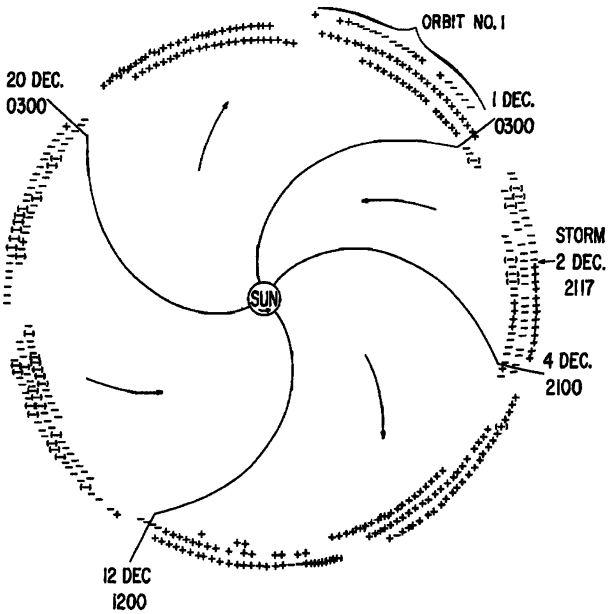
### 3.3 Sector Boundary

Wilcox and Ness (1965) and Schatten et al. (1969) found that large-scale magnetic structures on the Sun are related to magnetic field observations at 1 au. More specifically, they showed that the field of 'away' from the Sun and 'toward' (seen from the Earth) the Sun at 0.6 solar radial distance are related to 'away' from the Sun and 'toward' the Sun at 1 au, respectively; the magnetic field at 0.6 solar radii is inferred from the spherical analysis of the photospheric field under the assumption that there is no electric current in the corona; this surface is called the *source surface* (see Fig. 11b).

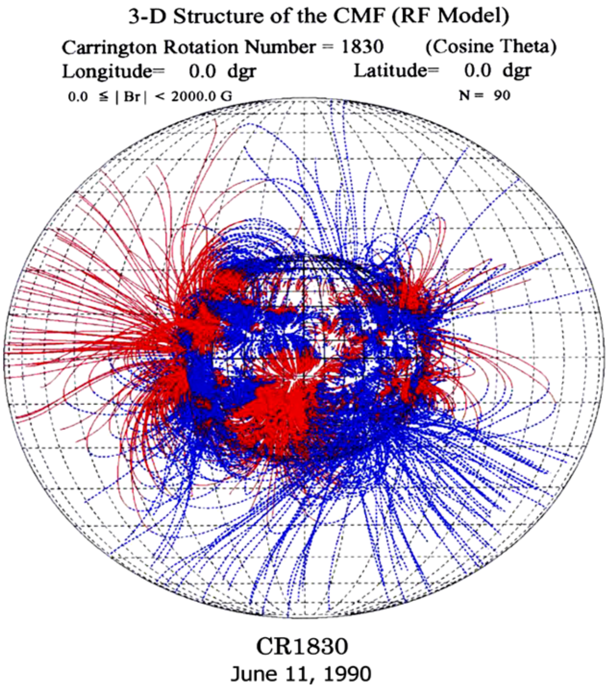
Thus they suggested a sector pattern of the interplanetary magnetic field. Figure 11a was constructed by Wilcox and Ness (1965). This is an example of the pattern that can be observed at the location of the Earth, namely near the solar equatorial plane. We can see in Sect. 3.4 that this sector structure is related to the equatorial cross-section of the warped current sheet. Figure 11b is a side view of the solar magnetic field to the distance of the source surface; it is assumed that all the field lines which can reach the source surface intersect perpendicularly with the source surface.

### 3.4 Warped Current Sheet

The three-dimensional structure of the interplanetary magnetic field in conjunction with the sector magnetic structure was suggested by Schultz (1973), Svalgaard and Wilcox (1975), and Alfven (1977). They envisaged a thin current sheet that separates the extended solar magnetic fields from the northern and southern region in interplanetary space. Schultz (1973) inferred that each reversal of the magnetic polarity (away and toward) at the Earth during each solar rotation is caused by the Earth's crossing of the current sheet as the Sun and the current sheet rotate. Figure 12 shows an example of the warped current sheet when the solar magnetic equator has one sinusoidal cycle (Akasofu and Fry 1986). A part of the



(a)



(b)

**Fig. 11** (**a**) The sector structure of the interplanetary magnetic field seen from the Earth. The interplanetary space is divided in terms of the magnetic field component pointing toward (+) the Earth and away (–) from the Earth (Wilcox and Ness 1965). (**b**) The side view of the solar magnetic field to a distance of the source surface (Courtesy of K. Hakamada)

Earth's orbit above the current sheet is shown. In such a case, the Earth crosses the warped current sheet twice during one solar rotation. When the magnetic equator has two sinusoidal cycles in solar longitude, the current sheet has a much more complicated shape; in such a

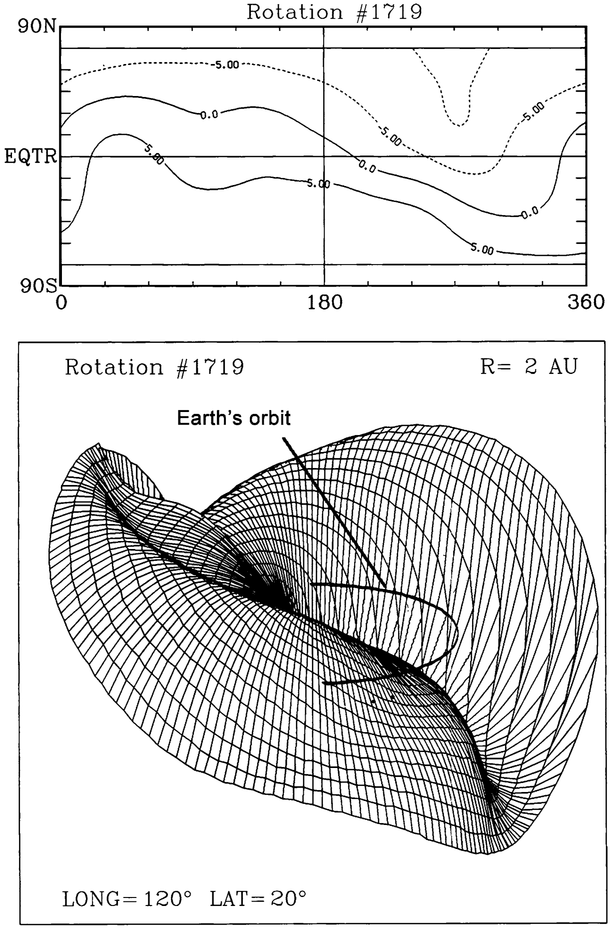



**Fig. 12** A typical example of the solar equatorial current sheet. In the upper part, the magnetic equator (0.0) of the Sun is shown. The current sheet originates from the solar magnetic equator; the Earth's orbit above the sheet is shown (Akasofu and Fry 1986)

case, the Earth crosses the current sheet four times as one can see in Fig. 11a. An example of the double crossing of the current sheet is shown in Fig. 12.

The reason for the warped structure of the current sheet is due to the fact that the current sheet is rooted at the magnetic equator of the Sun and that the magnetic equator seen on the source surface varies considerably during the sunspot cycle, as explained shortly. It divides the magnetic polarity, above the away sector and below the toward sector or vice versa (when the polarity changes in association with the sunspot cycle). The current sheet is nearly flat only during the period of sunspot minimum, when the magnetic equator nearly coincides with the solar equator, so that source surface mappings are dominated by the open field from the polar coronal holes.

As the solar cycle progresses, the solar magnetic equator inferred on the source surface varies considerably. The dipole axis inferred on the source surface rotates by 180° by the end of each cycle, so that the polarity of the dipole field is reversed during each cycle (Fig. 13a). Figure 13b shows the shift of the magnetic pole (in this case from north to south) during a sunspot cycle.

It should be noted, however, that the magnetic polar region on the photosphere remains near the pole. Unlike the field on the source surface, the photospheric dipole field does not

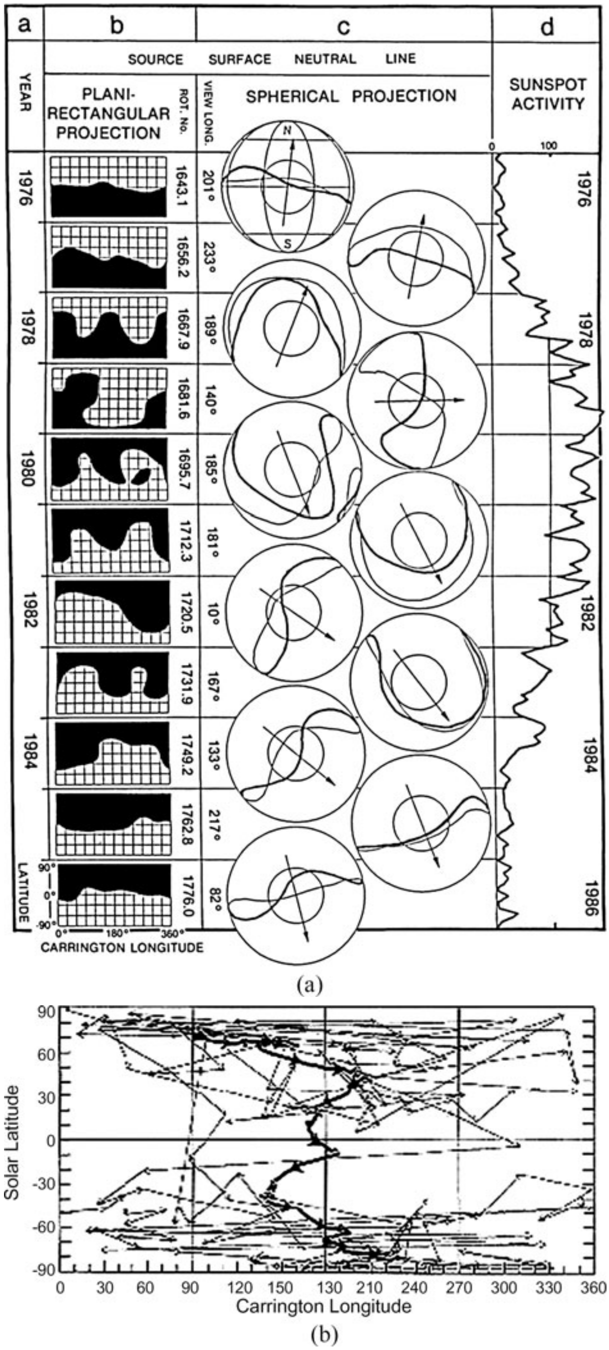



**Fig. 13** (**a**) From the *left*, the solar magnetic northern and southern hemispheres (*white*, toward the Earth, *black* away from the Earth), the magnetic equator and the orentation of the solar dipole field seen at a distance of 3 solar radii and the sunspot number (Saito et al. 1989). (**b**) The average movement (*thick line*) of the location of the pole during the sunspot cycle (Hakamada 2010)

rotate during the sunspot cycle. The evolution of the polar coronal holes during the sunspot cycles 22 and 23 was examined in detail by Harvey and Recely (2002).

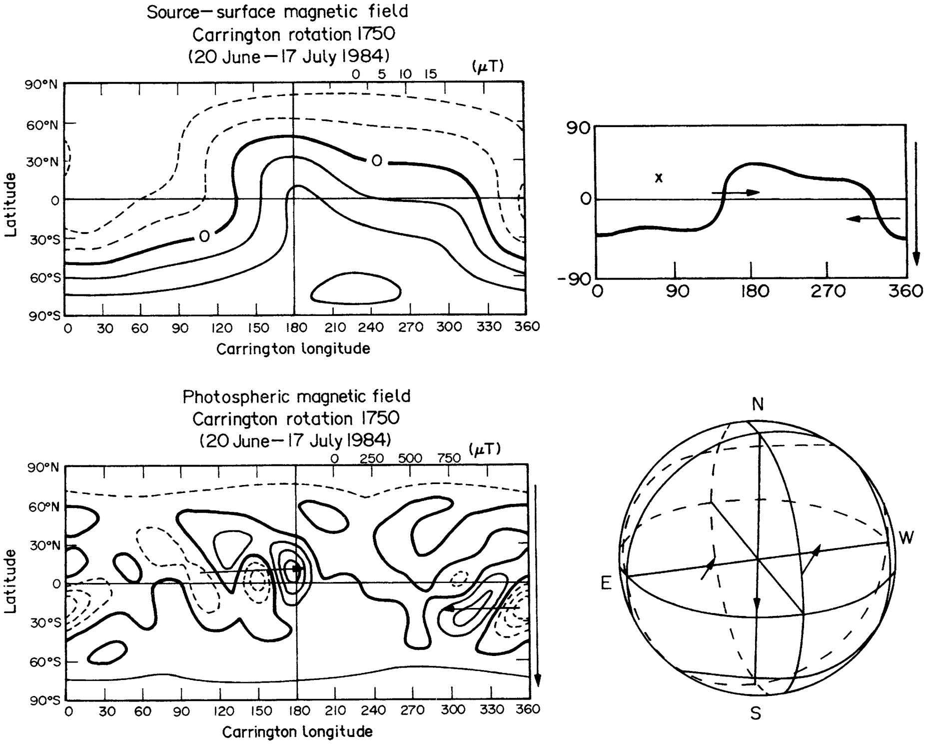



**Fig. 14** From the *upper left*, the solar magnetic equator, the *lower left*, two dipole fields which appeared near the sunspot maximum: *Upper right*, the computed magnetic equator with the dipole and the two equatorial dipoles shown in the lower right; note a fairly good agreement with the observed one in the *upper left* (Saito and Akasofu 1990)

The reason for the apparent rotation of the dipole field seen at a distance of a few solar radii appears to be related to the fact that there appear one or two dipolar field(s) near the solar equator of the photosphere, which is almost perpendicular to the dipole axis (Fig. 14); it grows and decays during a sunspot cycle. It is likely that the combined field vectors of the solar dipole and the growth and decay of this additional equatorial dipole on the photosphere results in the apparent rotation of the dipole field on the source surface (Saito and Akasofu 1990); see Fig. 14. The magnetic equator on the source surface lies almost in a meridian plane around the sunspot maximum period and the equatorial dipole is directed almost perpendicular to the rotation axis (see Figs. 13a and 13b); this was the reason why the current sheet was considered earlier as the sector (meridional) boundary. Note that the reversal of the main photospheric dipole is caused by the poleward migration of the UM field.

### 3.5 Meridional Interplanetary Magnetic Structure

In spite of the above progress, we are still uncertain about the meridional structure of the interplanetary magnetic field. This question is closely related to the source region of the quiet-time solar wind (more specifically, the solar latitude), which reaches the Earth or near the solar equatorial plane. A model of the interplanetary field in a longitudinal cross-section

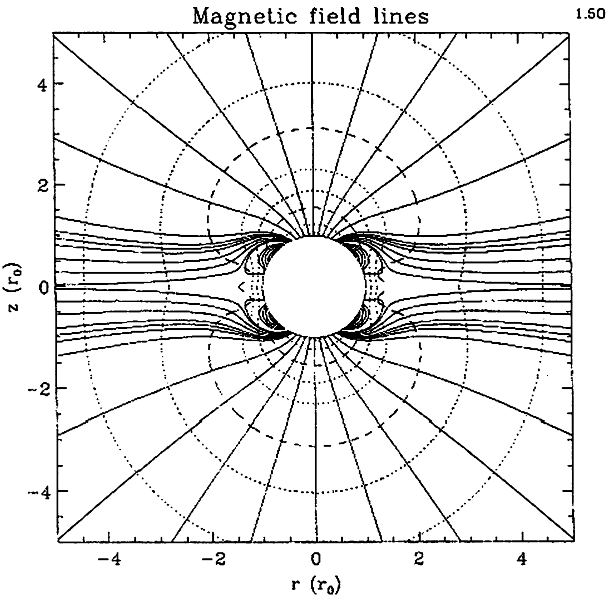



**Fig. 15** Meridian view of the model interplanetary magnetic field during the sunspot minimum period. Note that the field lines near the boundary of the polar coronal holes reaches low latitudes (Banaszkiewicz et al. 1998)

is shown in Fig. 15 for a solar minimum condition. It is likely that the quiet-time solar wind observed at the location of the Earth blows out from higher latitudes, perhaps near the boundary of the polar coronal hole. It is crucial to know the origin of the interplanetary magnetic field at least at the Earth's location. In this situation, because the magnetic equator and the equator coincide, there is a flat current sheet rooted at the equator, dividing the away sector and the toward sector.

## 3.6 Simulation of Recurrent Geomagnetic Disturbances

The progress described in the earlier sections now enables us to simulate recurrent geomagnetic disturbances discovered by Maunder (Sect. 1.4). The recurrent geomagnetic disturbances in 1974 can be reproduced by assuming a sinusoidal magnetic equator on the source surface and a higher speed at higher latitudes (see Fig. 6a). In this case, it is assumed that the northern coronal hole extends across the solar equator and the southern polar coronal hole extends to the northern hemisphere (Fig. 9). This was the situation of the coronal holes in 1974 when the extended holes were separated by 180° in solar longitude.

In Fig. 16, it is assumed that the solar wind speed is minimum (300 km/sec) along the magnetic equator and becomes higher toward higher latitudes (see Fig. 6a). At a point fixed in space (not to the Sun) at a distance of 2 solar radii, the observed solar wind speed has two maxima, 90° and 270° in longitude in one solar rotation. It is shown in the lower half of Fig. 16. After solar wind particles leave the Sun, a faster flow pushes a slower flow, generating a shock wave at some distance beyond the Earth (Hundhausen 1972). As a result, the flow speed shown in the lower half of Fig. 16 becomes distorted, as shown in the top of Fig. 18a. The IMF structure within 2 au on the equatorial plane is shown in Fig. 17. The shock waves co-rotate with the Sun.

Figures 18a and 18b show the simulated and observed solar wind speed and the IMF at the location of the Earth, respectively. A shock wave-like structure appears at about the time of the current sheet crossing because a faster flow interacts with a slow flow; the shock wave

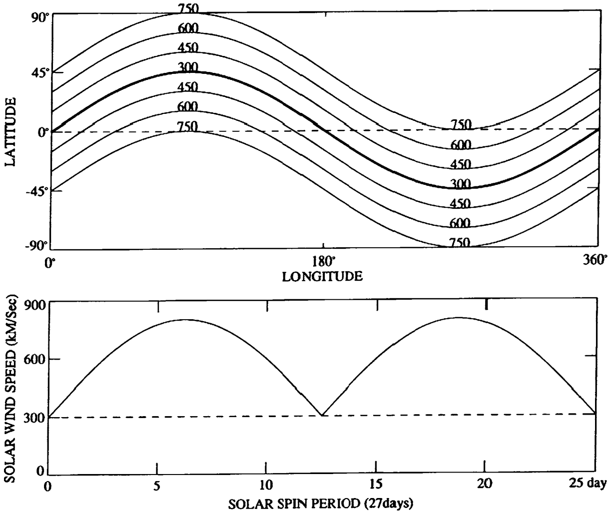



**Fig. 16** *Upper*, the solar wind speed distribution on the photosphere, and *Lower*, the speed variation during one solar rotation, at a point fixed in space (not on the solar surface) (Hakamada and Akasofu 1982; Akasofu 1983)

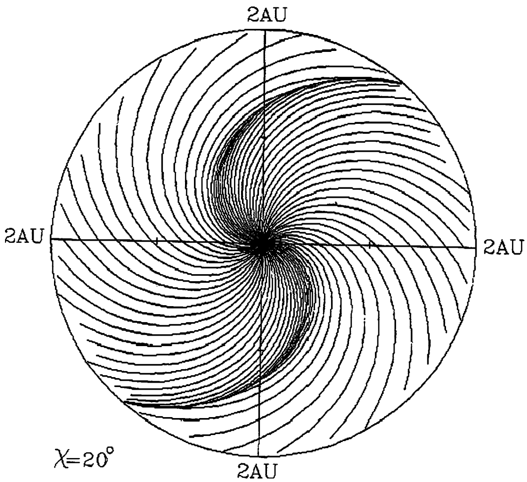
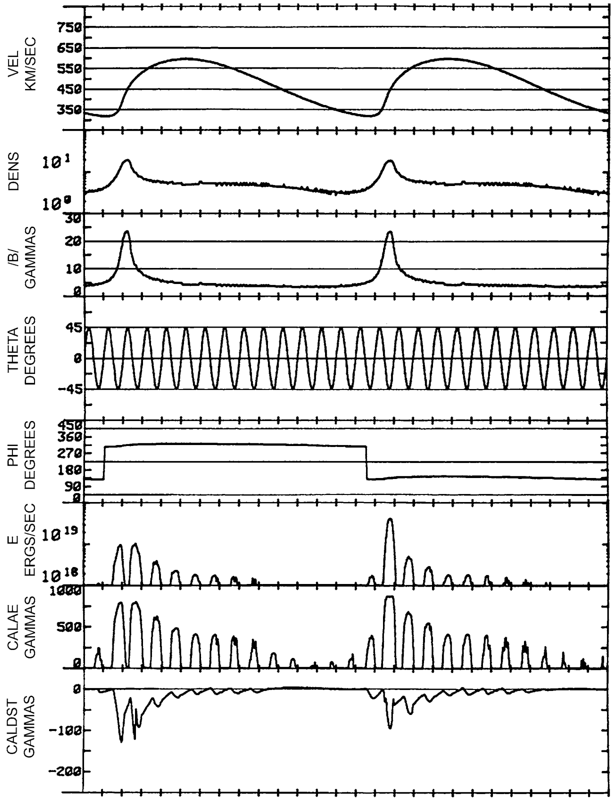



**Fig. 17** The interplanetary magnetic field lines for the condition given in the *upper part* of Fig. 12. Note the two co-rotating structure where the polarity of the interplanetary field changes, from away to toward or vice versa (Hakamada and Akasofu 1982)

may form beyond a distance of about 1.5 au (see Fig. 17). Figures 18a and 18b show that the time of arrival of the faster flow coincides with that of the interplanetary (equatorial) current sheet. This is indicated in the sudden change of the azimuth angle (PHI), the current sheet crossing. At the current sheet crossing, the solar wind speed increases rapidly, and both the number density and the IMF magnitude show an impulsive increase.

The latitudinal component of the IMF (Theta) is assumed to have sinusoidal fluctuations, simulating irregular changes (including Alfven waves). The resulting geomagnetic disturbances can be simulated in terms of the standard AE and Dst indices because we can infer the power (E) generated by the solar wind-magnetosphere interaction on the basis of the observed speed $V$, the IMF magnitude $B$, and the polar angle $\theta$ (see Sect. 8.1); the power (E) is shown in the sixth row in Figs. 18a and 18b. Comparing Figs. 18a and 18b, one can see that the resulting recurrent geomagnetic disturbances can be reasonably well simulated; for the AE and Dst indices, see the caption of Fig. 3c.




(a)

**Fig. 18** (**a**) From the *top*, the simulated solar wind speed, density the magnetic field magnitude, the vector angle with respect to the equator, the azimuthal angle at 1 au and the expected changes of the solar wind-magnetosphere coupling function E (see Sect. 8), and geomagnetic indices AE and Dst (Hakamada and Akasofu 1982; Akasofu 1983); for the AE and Dst indices, see the caption of Fig. 3c. (**b**) This observed data set corresponds to Fig. 18a (except that PHI is reversed)

## 4 Interplanetary Shock Waves Caused by Solar Activities

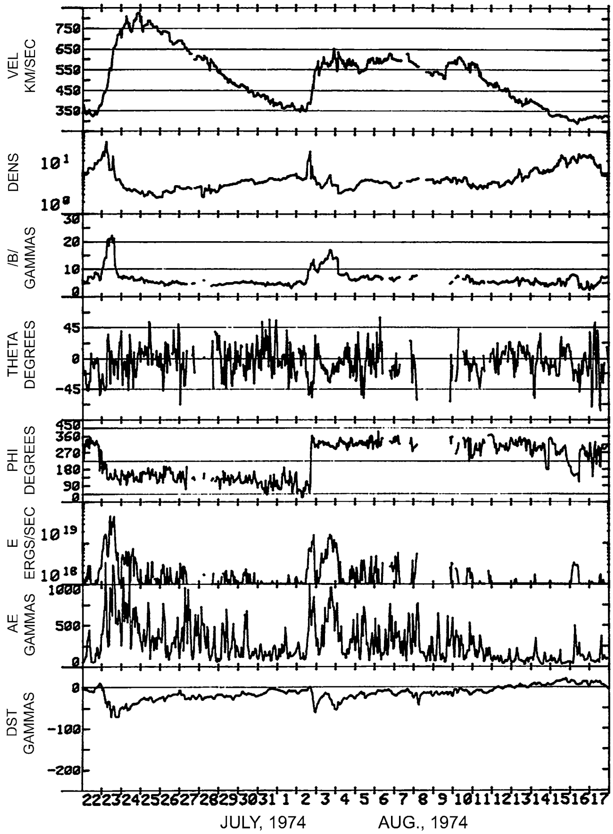
### 4.1 Interplanetary Shock Waves

As mentioned in Sect. 2.2, Chapman and Ferraro (1931) successfully explained the storm sudden commencement (ssc) as a result of the impact of an enhanced solar wind; it is a step function-like increase of the horizontal component of the field. The first two records in Fig. 19 show the IMF magnitude $B$ and the north-south component $Bz$. The arrival of the shock wave is clearly seen in the magnitude $B$. The lower two records show the combined magnetic records from high latitude stations and low latitude stations, respectively. The sudden commencement is seen clearly in the low latitude records. Note also that an intense geomagnetic storm developed after $Bz$ became negative, namely the southward turning of the IMF vector; see Sect. 8.

### 4.2 Gold's Hypothesis

Gold (1955) associated the ssc with the impact of a shock wave, which propagates in interplanetary gas, instead of a direct impact of solar plasma flows on the Earth's dipole field. During a symposium entitled "Gas Dynamics of Cosmic Clouds" (p. 104) held at Cambridge, England, July 6–11, 1953, he stated:

**Fig. 18** (*Continued*)




(b)

> I should like to discuss, in connection with the subject of shock waves, some of the magnetic disturbances on the Earth that are caused by solar outbursts. The initial magnetic disturbance at 'Sudden Commencement' of a magnetic storm can be accounted for very roughly by an increase of pressure of the tenuous gas around the Earth. This increase of pressure may perhaps be described as the effect of a wave sent out by the Sun through the tenuous medium between Sun and Earth. In the complete absence of any such medium this description would then correspond to that of a stream of particles, while in the presence of a medium the correct description may lie anywhere between an acoustic wave, a supersonic shock wave or an unimpeded corpuscular stream. The observations of magnetic storms may hence give us a fairly direct proof of the existence of shock waves in the interplanetary medium.

However, Liepman (1955) objected to Gold's suggestion:

> I would ask whether the picture of a shock wave really is applicable. The mean free path in the residual gas between the Sun and the Earth appears to be 4 or 5 times the solar radii .... In order to get agreement with Gold's values the mean free path would have to be considerably shorter, i.e. by a ratio of 100 or else the medium of interaction of the wave with the field of the Earth has to explain the very sudden rise observed.

Gold refuted this objection by stating:

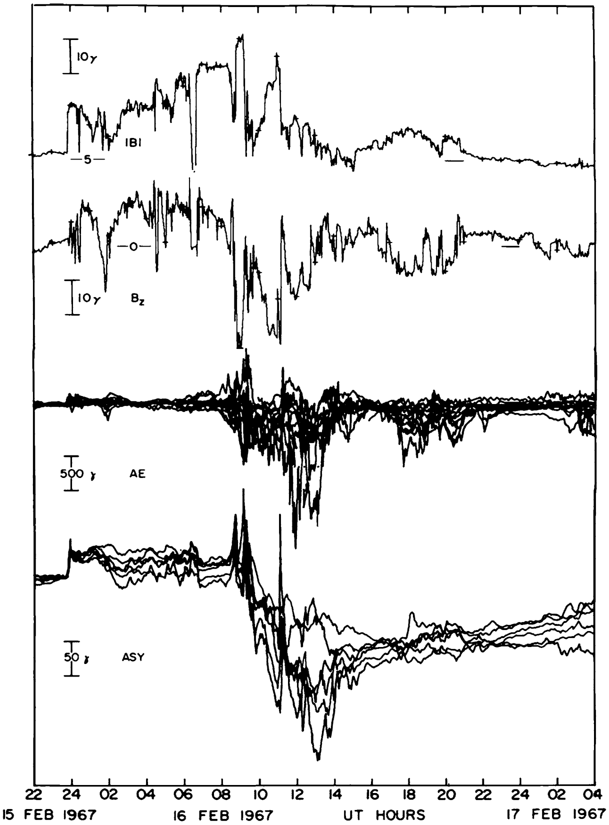



**Fig. 19** An example of geomagnetic storms. In the *upper part*, IMF record ($B$ and $Bz$) is shown, indicating the arrival of the interplanetary shock wave. In the *lower part*, a combined geomagnetic record from high latitude stations and low latitude stations. Note the ssc occurred at the time of the arrival of the shock wave, and an intense geomagnetic storm began when the IMF $Bz$ became negative (southward turning); see also Sect. 5.2

> In considering the interaction between the stream and the residual gas one must not restrict oneself to the collision cross section of neutral particles, but one has to consider the much stronger electromagnetic interactions that may occur between the two ionized gases.

In fact, the gyro-radius of protons and electrons is more important than the mean free path in determining various transport coefficients. In order to explain the propagation of the shock wave, Parker (1961) postulated the propagation of blast waves which are generated by solar activities. His theory has been extended by Hundhausen and Gentry (1969), Dryer (1975), and many others. However, it is not likely that the shock waves generated by solar flares are blast waves, but are driven by what is called the 'driver gas.' The reason for this development is explained in Sect. 5.3.

Akasofu and Yoshida (1967) examined the solar longitudinal dependence of the magnitude of the storm sudden commencement of geomagnetic storms. Figure 20 shows the dependence of the magnitude of ssc on the solar longitude.

Based on the results in Figs. 20 and 25, they proposed the structure of solar plasma flow generated by solar flares. It consists of a shock wave and the gas driving the shock. Their figure is reproduced as Fig. 21. Note that the gas cloud is detached from the Sun in this model.

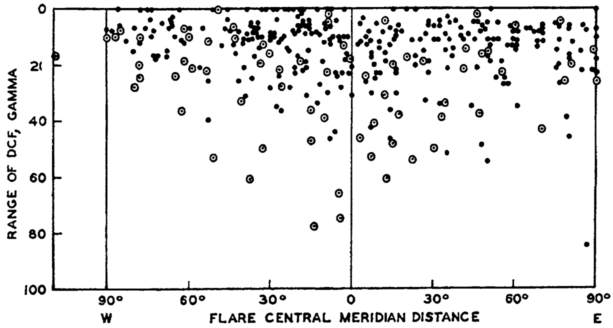



**Fig. 20** The magnitude of storm sudden commencement as a function of the solar longitude of responsible solar flares; *circles* with *dots* indicate flares associated with the polar cap absorption (Akasofu and Yoshida 1967)

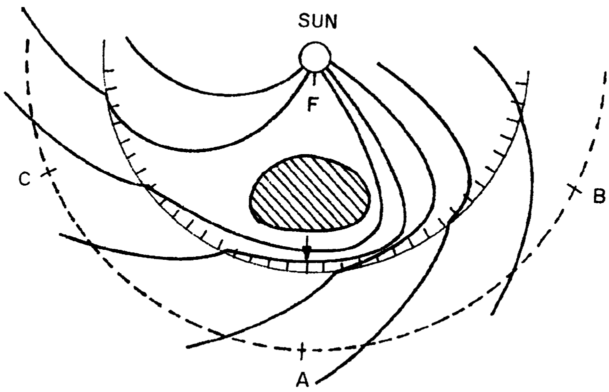



**Fig. 21** An example of early models of the driver gas and the shock wave driven by the driver gas. Depending on the location of the Earth, A, B and C, the storm intensity is different (Akasofu and Yoshida 1967)

## 4.3 Observations and Simulations

There were some early efforts to detect the advancing shock waves by using the interplanetary scintillation method. Figure 22 shows the observed scintillation in the sky on September 24, 1978, by Hewish et al. (1985); see the lower right diagram of Fig. 22. Both the upper right and left diagrams of Fig. 22 show the simulated shock wave. The simulated shock wave is projected in the sky map in the lower left (Akasofu and Lee 1989, 1990). Comparing the two lower diagrams in Fig. 22, one can see that the results are in reasonably good agreement. This example provided a possible opportunity to observe the advancing shock approximately 24 hours before its arrival to the Earth, since it takes in general about two days for the shock to propagate from the Sun to the Earth.

For a more recent scintillation study, see Manoharan (2010). The configuration and propagation of the shock front was simulated for a number of researchers (cf. Wu et al. 1979; Dryer et al. 2004). Figures 23a and 23b show examples of the simulation results (Akasofu and Lee 1990; Akasofu 1996). The observations were limited by the number of spacecraft and their position. However, the simulation can provide a larger scale of view, together with the interaction between the co-rotating structure and shock waves.

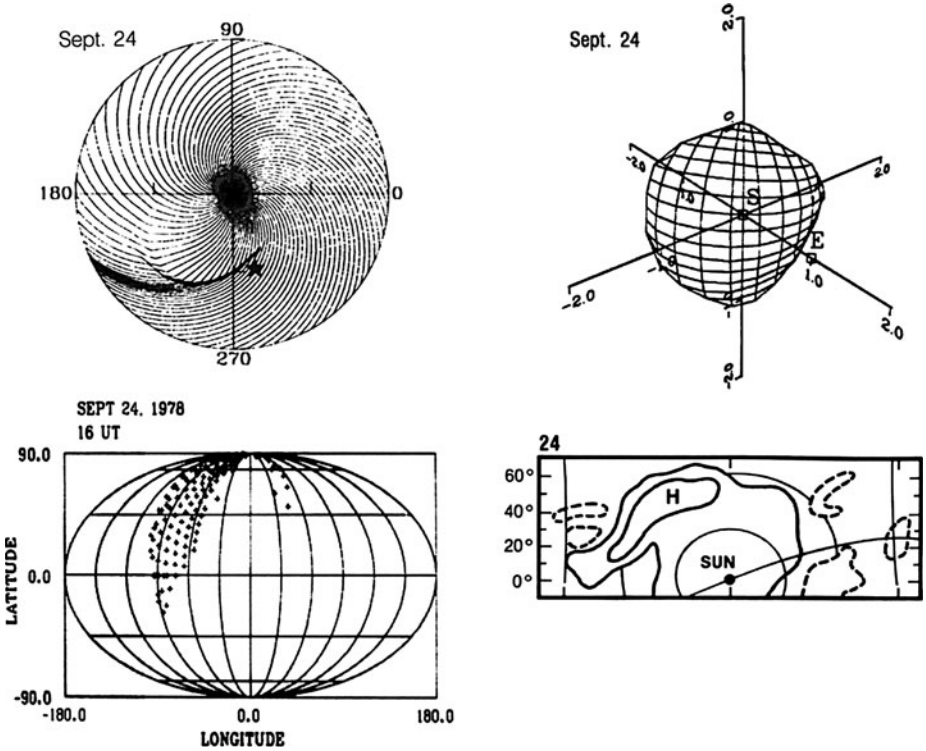



**Fig. 22** The shock wave on September 24, 1967. The observation and the simulation. For details, see the text (Akasofu and Lee 1989)

## 5 Driver Gas

### 5.1 Doubts About Solar Flares as a Cause of Geomagnetic Storms

Until 1943, there were some doubts about solar flares as a source of geomagnetic storms. These doubts arose because many intense flares did not necessarily cause geomagnetic storms. Newton (1943) clarified a part of this puzzle by finding that solar flares near the central meridian tend to cause most intense storms, while limb flares may cause only weak magnetic disturbances (see Fig. 24). Figure 25 is constructed on the basis of more data and shows that it is true that solar flares near the central meridian tend to produce intense geomagnetic storms, but many do not (Akasofu and Yoshida 1967). It should be noted that in constructing Fig. 25, it was difficult to identify the source flare for a given geomagnetic storm when intense flares occur successively; each point in the figures is carefully chosen, inferring the propagation time.

Many space physicists today are unaware of Newton's 1943 study and forecast major geomagnetic storms and auroral displays after intense flares located even far from the central meridian. Further, it will be shown in Sect. 8 that there is one more crucial parameter that determines the intensity of storms, the polar angle of the IMF $\theta$ or the north or southward components of the interplanetary magnetic field.

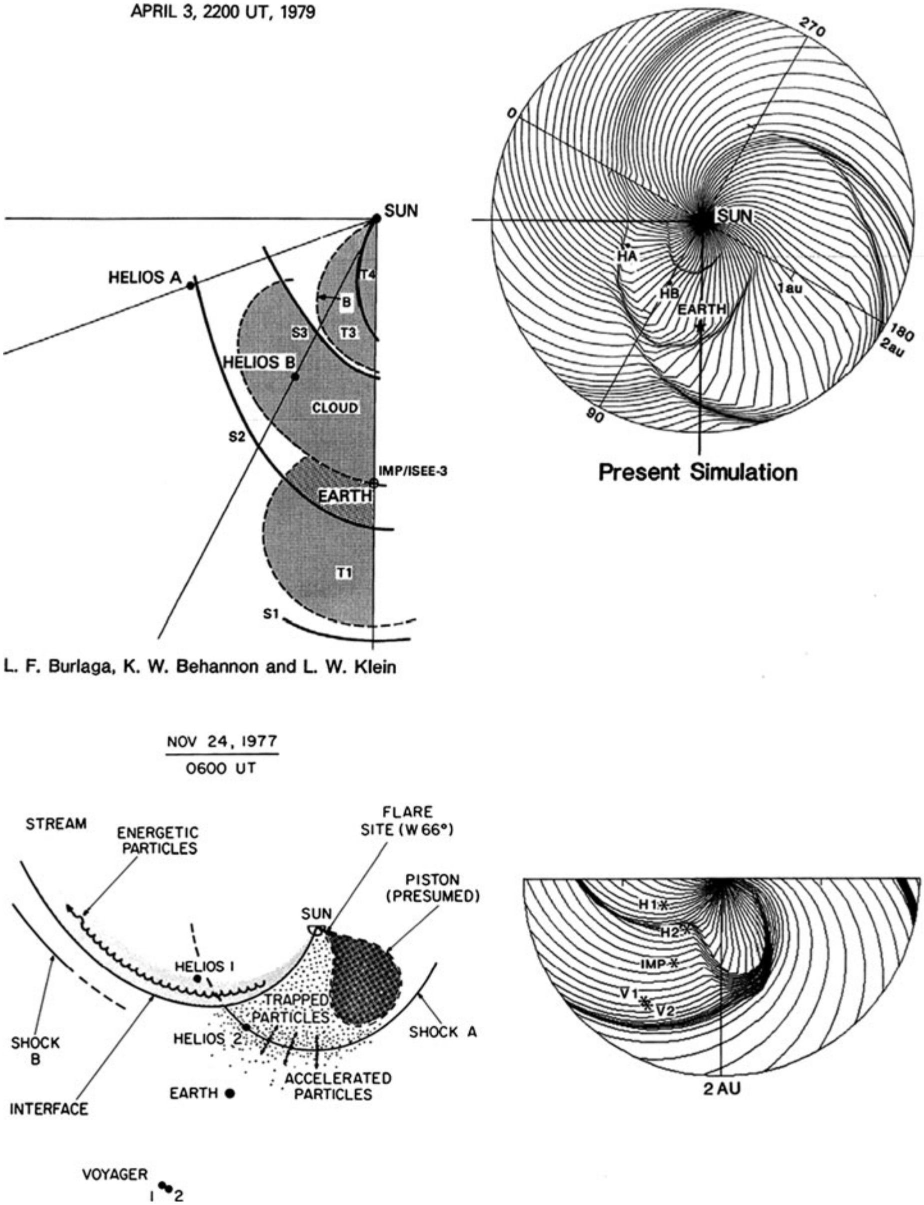



**Fig. 23** The observed shock waves and the simulated ones. The simulation can provide a wider view of the shocks (Akasofu and Lee 1990; Akasofu 1996)

## 5.2 Solar Filaments

One of the fundamental issues of the origin of solar plasma flow generated by solar flares is what parts of the solar atmosphere are ejected at the time of solar flares. In this section, it is shown that this problem still remains today despite great progress in solar observations in recent years.

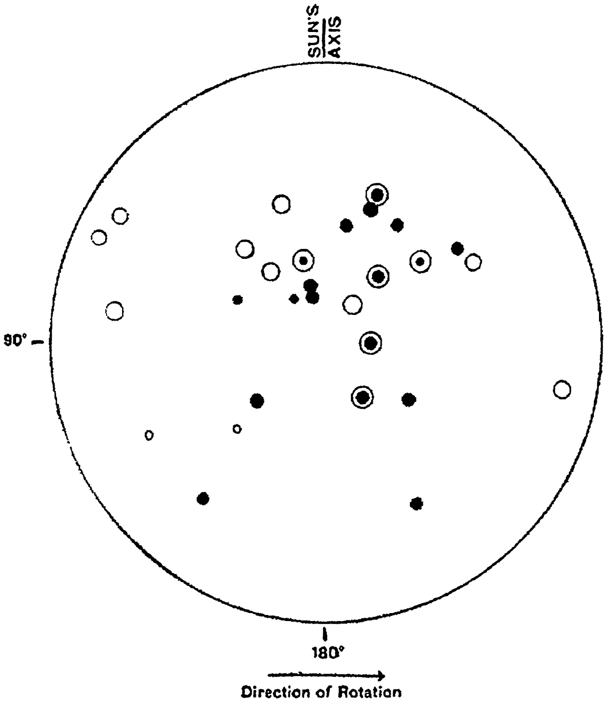



**Fig. 24** Newton (1943) showed that solar flares causing intense geomagnetic storms occur around the central meridian (the differences of the *dots* and *circles* appear to be indicating the differences of the intensity of geomagnetic storms; Newton noted that the *open circles* are related to small storms)

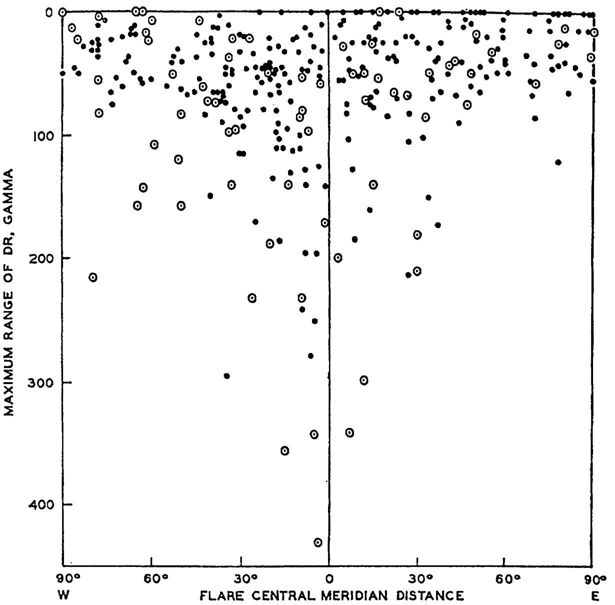



**Fig. 25** The dependence of the Dst index as a function of the responsible solar flare longitude; *circles* with *dots* indicate solar flares associated with the polar cap absorption (Akasofu and Yoshida 1967)

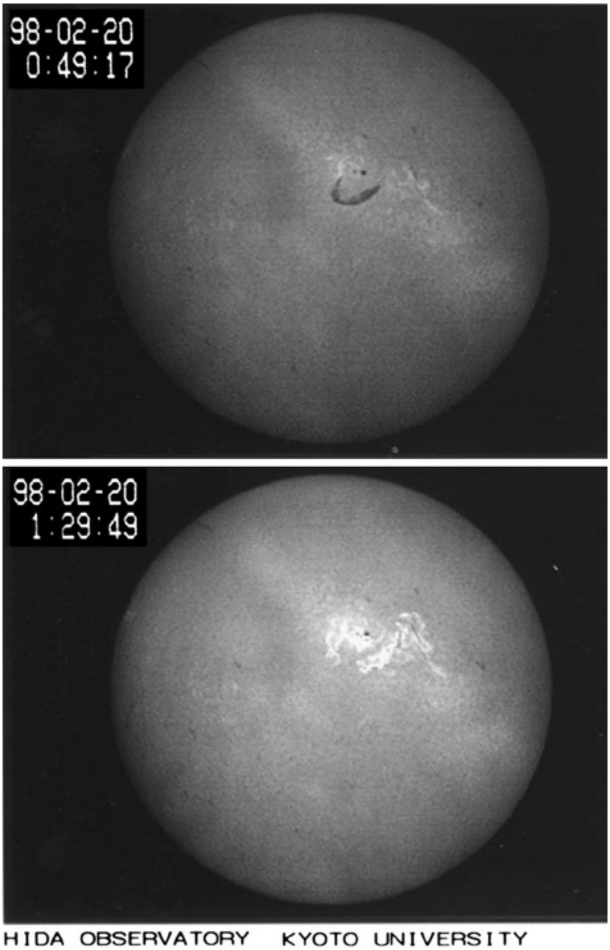
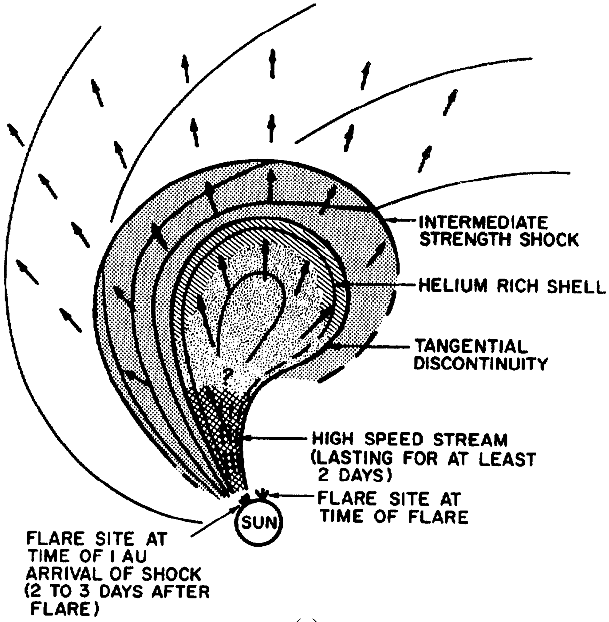



**Fig. 26** An example of the disappearance of dark filament associated with a solar flare (Courtesy of Kyoto University Solar Observatory)

Among flares, some are associated with a sudden disappearance of dark filaments in the chromosphere or in the lower corona. Figure 26 shows such an example. This does not necessarily imply that the disappearing filaments are responsible for initiating solar flares. Rather, it is likely that the filaments are sitting on an arch-like magnetic field structure and are blown away at the time of solar flares. An important point is that the filament has a dark string-like structure and, in fact, when seen above the limb of the Sun, it is a very bright feature, emitting the H alpha line, indicating that neutral hydrogen atoms are present there. It has been speculated that the suddenly disappearing filament itself is the driver gas, or at least that it triggers interplanetary disturbances (cf. Joselyn and McIntosh 1981). This subject is related to the observations of $He^+$ and H in the disturbed solar wind (Sect. 5.3) and the magnetic structure of coronal mass ejections (Sect. 6.2). This type of flares is mentioned here because it may be related to the subject of the next section. Further, it appears that the filaments have helical magnetic fields which are important in understanding the configuration of magnetic fields in magnetic clouds (Sect. 6.2); see also Akasofu (2007, Chap. 8).




(a)

**Fig. 27** (**a**) A newer model of the driver gas, including the helium layer (Hundhausen 1972). (**b**) Shows a great variety of the development of geomagnetic storms. It shows that the intensity of the main phase decrease represented by the magnitude of the main phase decrease does not depend on the size of storm sudden commencements which represent the pressure of the solar wind

## 5.3 Helium-Rich Layers and the Observation of Neutral Hydrogen Atoms

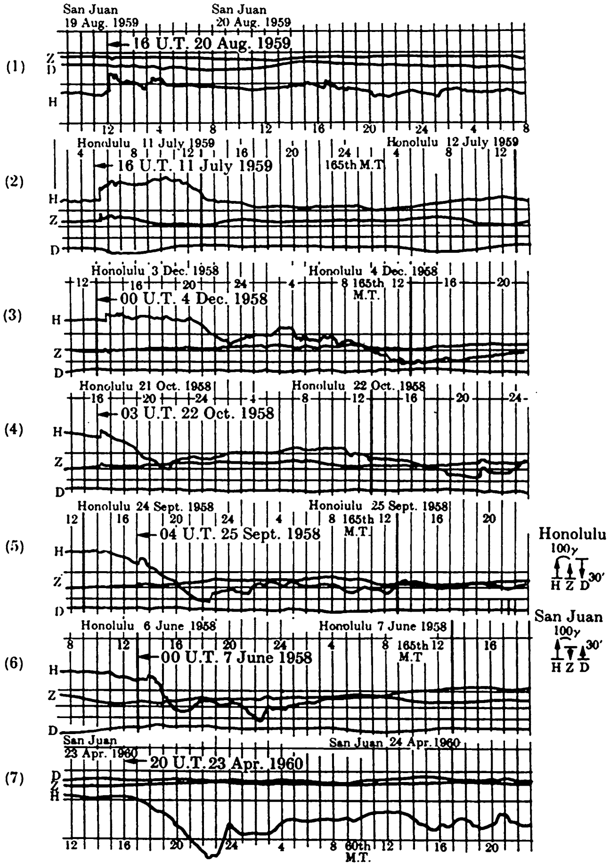
Hirshberg et al. (1970) found a helium-rich shell behind the interplanetary shock wave. This occurred after a Class 3B flare on February 13, 1967. Hirshberg et al. (1970, 1971, 1972) have suggested that the Sun ejects a high-speed cloud of the chromospheric (helium-rich) gas that generates the interplanetary shock wave as it interacts with the quiet-time solar wind.

Hovestadt et al. (1981) found that the ratio $He^+/He^{++}$ was as high as 0.04 to 0.21 after three flares. In the corona, because of its high temperature, this ratio is $10^{-4}$ or much less in the quiet solar wind. This high ratio was confirmed by Gosling et al. (1980). It is generally believed that solar plasma flow is fully ionized. "Nevertheless," they noted, "the rare appearance of $He^+$ in the solar wind at 1 AU as reported here indicates that a search for other ionizationally cool ionic species in postshock flows may be worthwhile." Furher, Skoug et al. (1999) observed a high ratio of $He^+/He^{++}$ (more than 0.5%), lasting for a period of more than 24 hours and suggested the presence of parts of filaments and prominences.

Thus the picture that emerges from the helium observations is that in larger particle-emitting flare events, a substantial fraction of "cold" chromospheric material, possibly during the eruptive phase of the flare, is injected into the acceleration region. The present concept of the driver gas is shown in Fig. 27a.

As a point of historical interest, Akasofu (1964) proposed that the variety of development of geomagnetic storms could be explained by assuming that the solar plasma clouds have different distributions of neutral hydrogen atoms, which can penetrate across the magnetopause and become ring current particles for the main phase (Fig. 36) after being ionized by charge exchange processes. His study was based on the fact that the intensity of the main phase of geomagnetic storms does not depend on the intensity of

**Fig. 27** (*Continued*)




(b)

the solar wind represented by the storm sudden commencement (ssc); see that the bottom storm in Fig. 27b was not preceded by a ssc. Akasofu and Chapman (1963) suggested:

> The variety of development of the storm seems to suggest some intrinsic differences between the solar streams far beyond what we would expect from a mere difference between their pressures. The nature of their differences is at present unknown.

Subsequently, Fairfield and Cahill (1966) found that the "unknown" factor suggested by Akasofu and Chapman (1963) is the southward oriented inter planetary magnetic field; see Fig. 19. Brandt and Hunten (1966) argued that neutral hydrogen atoms cannot survive on their way to the Earth and become ionized by the solar radiation. On the other hand Collier et al. (2001) observed neutral atoms in the solar wind at the time when its speed suddenly jumped (Fig. 28). It is likely that the neutral atoms are hydrogen atoms.

These observations suggest that driver gases are not necessarily fully ionized at least in some cases, so that such observations might provide a clue about the height of the solar atmosphere, namely from which height driver gases originate or the role of the dark filaments in driver gases.

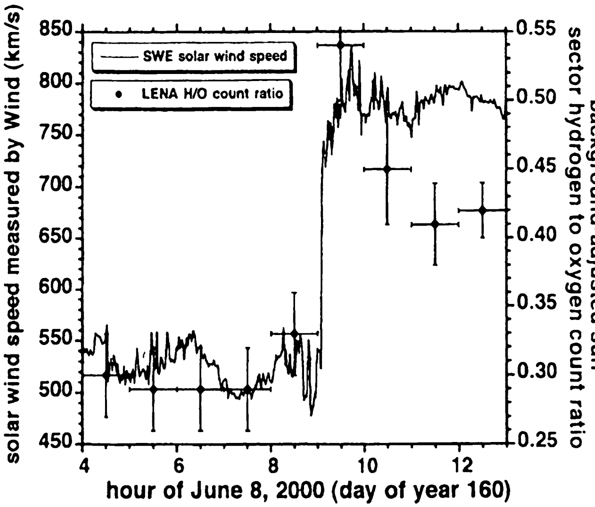



**Fig. 28** An observation of the neutral hydrogen flux in the solar wind (Collier et al. 2001)

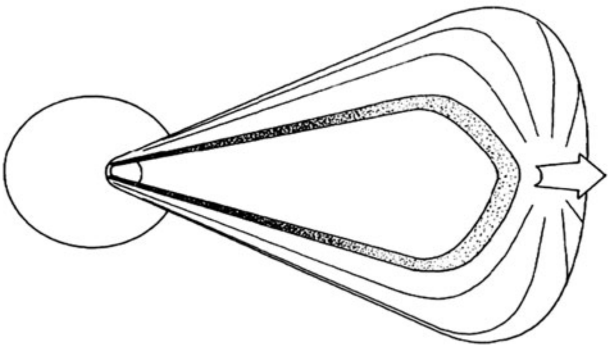


**Fig. 29** One of the earlier suggestions of the CME (Howard et al. 1982)

## 6 Coronal Mass Ejections (CMEs): Bubbles, Ropes, or Loops?

Section 5 described how the concept of driver gases was developed. It was one of the steps in developing the concept of coronal mass ejections (CMEs), which include magnetic fields. CMEs are one of the most studied subjects these days and a few monographs are available (cf. Kunow et al. 2006; Crooker et al. 2009). There is a fundamental issue of the relationship between solar flares and CMEs (namely, how CMEs are ejected), but it is beyond the scope of this paper; see also the Summary section.

### 6.1 Early Observations

It has long been speculated that part of the solar corona, the uppermost part of the solar atmosphere, is blown out at the time of intense solar activities. One of the earliest identification of CMEs, as transients in the corona, was made by Tousey (1973) on the basis of OSO 7 white light corona and the XUV (171-630) observations. A large number of coronagraph observations have supported such a hypothesis (Howard et al. 1982) (Fig. 29).

### 6.2 Magnetic Clouds

Gosling et al. (1973) found anomalously low proton temperatures in the solar wind following interplanetary shock waves and suggested a magnetic bottle within the ejecta. Subsequently, Burlaga et al. (1981) found that there is a magnetic loop behind the shock wave on the basis of data from several satellites/space probes. They found that the magnetic field vector changes in a way that is consistent with the passage of a magnetic loop which contains a helical magnetic structure (see also Burlaga 1995). There have been a large number of observations that show various types of helical structures. In the helical structure, both the density and temperature of the plasma are low. They called it a magnetic cloud. Gosling et al. (1986, 1991) suggested that some of the magnetic loops have their feet on the photosphere on the basis of bi-directional electron streams along the loop. Such a helical structure requires field-aligned currents along the magnetic field loop. The current intensity is estimated to be about $10^9$ amperes by assuming that the loop has a radius of about 0.2 au and the speed 700 km/sec and IMF magnitude 10 nT. An example of the simulated loop is shown in Fig. 30a. It is based on the observation shown in Fig. 30b. Comparing Figs. 30a and 30b, one can see that the simulation can reproduce the observation fairly well.

Magnetic clouds observed in interplanetary space are often called ICMEs, in which 'I' signifies 'interplanetary'. However, note that CMEs are observed optically near the Sun, and we are still uncertain about the optical feature of CMEs in interplanetary space (Sect. 6.3) and are waiting for results of the STEREO project; magnetic clouds are only a magnetic component of CMEs.

### 6.3 Topology

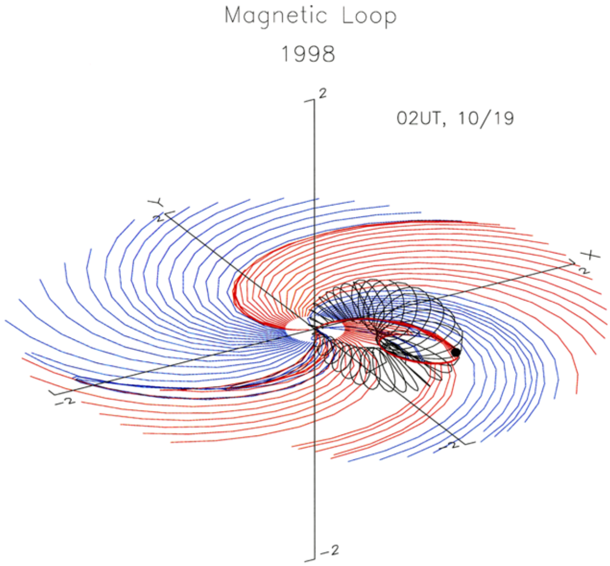
There has been an attempt to obtain the topology of CMEs through an optical method by Jackson (1997) and a scintillation method by Manoharan (2010). Although a large number of events have been observed and these results are analyzed in detail, there is so far considerable uncertainty about the topology of CMEs; it is either a bubble, a rope, loops, or a partial spherical surface in terms of optical observations (causing a halo CME). The STEREO observation is ideal in examining this topology. Figures 31a and 31b show a simulation of a hypothetical shock wave from the two STEREO spacecraft and one earth-bound spacecraft located in the ideal configuration (see also Kunow et al. 2006). A few recent examples to simulate the transit of CMEs are shown in Figs. 32a, 32b, and 32c; see Titov and Demoulin (1999), Odstrcil et al. (2004), Roussev et al. (2007), and Lugas et al. 2009).

Because of the complexity of CMEs, this subject requires a close working relationship between observers/analysis and simulation researchers. Individual solar flares must provide their individual initial conditions for each simulation, because individual flares are so different.

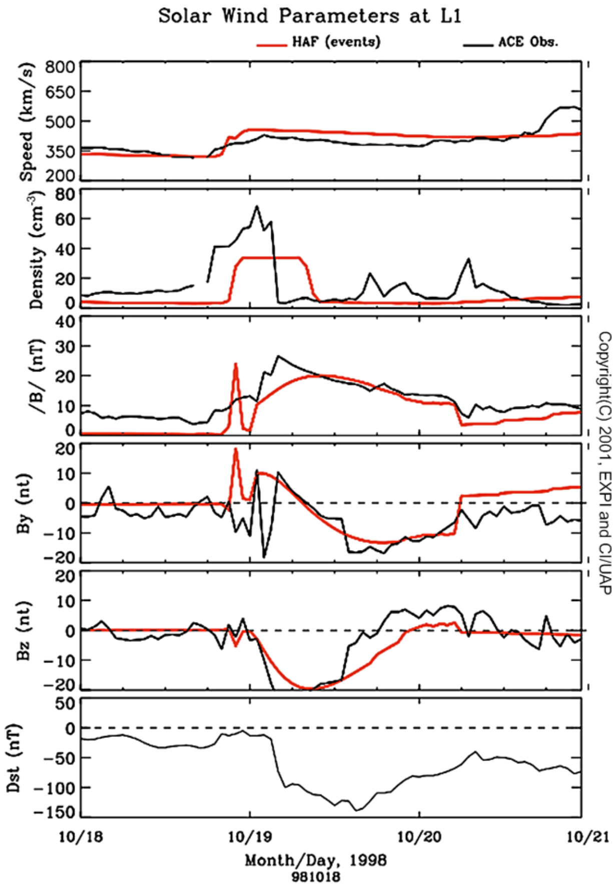
## 7 Cosmic-Ray Changes

There is a well-established anti-correlation between the 11-year cycle sunspot number and the cosmic-ray intensity (Fig. 33). Further, it is known that geomagnetic storms are often associated with a sudden decrease of cosmic-ray intensity, called the Forbush effect. It is likely that this cosmic-ray change results from accumulated shock/magnetic cloud assemblies, acting like a barrier for cosmic ray particles penetrating into interplanetary space (Fig. 34).

**Fig. 30** (**a**) Simulated magnetic cloud, the helical structure, associated with the storm of May 15, 1998; the *red lines* indicate the field lines directed away from the Sun, the blue lines toward the Sun (Saito et al. 2007). (**b**) The observed (*black lines*) and simulated (*red lines*) changes of the solar wind during the geomagnetic storm (Dst index) of May 15, 1998. The associated magnetic cloud is shown in (**a**) (Saito et al. 2007)




(a)




(b)

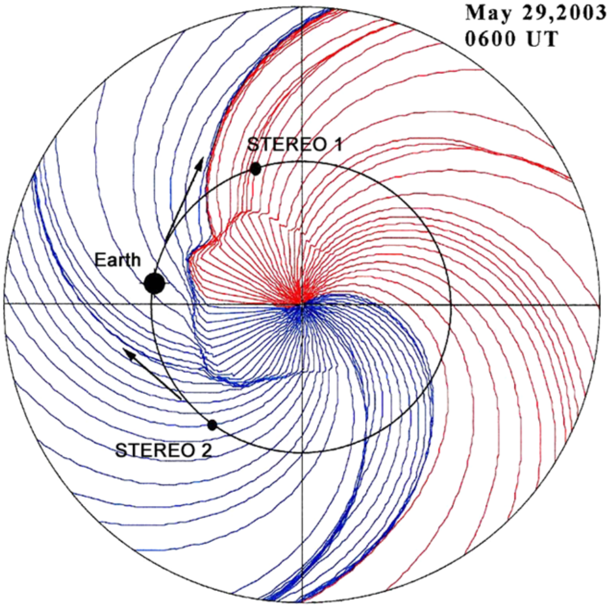



**Fig. 31** (**a**) The location of the Earth (the *large dot*) and two STEREO spacecrafts (the *small dots*) and a simulated shock wave; the *red lines* are the field lines directed away from the Sun and the *blue lines* toward the Sun (Sun et al. 2008). (**b**) The simulated shock front at the location of the STEREO spacecraft and the Earth; their locations are shown in (a) (Sun et al. 2008)

## 8 Geomagnetic Storms

Since the whole effort of studying the solar-terrestrial relationship began in order to understand geomagnetic storms, it may be worthwhile to review briefly the present understanding of geomagnetic storms (cf. Akasofu and Chapman 1972).

### 8.1 The Importance of Magnetic Clouds in Causing Geomagnetic Storms

It is now understood that major geomagnetic storms result from the interaction between CMEs (particularly magnetic clouds) and the magnetosphere. A weaker geomagnetic storm is caused by streams from the coronal holes (Sect. 3.4).

The interaction between magnetic clouds and the magnetosphere is basically a dynamo process that converts the kinetic energy of the solar wind particles into electric power (cf. Akasofu 1981). The power $\varepsilon$ is given by

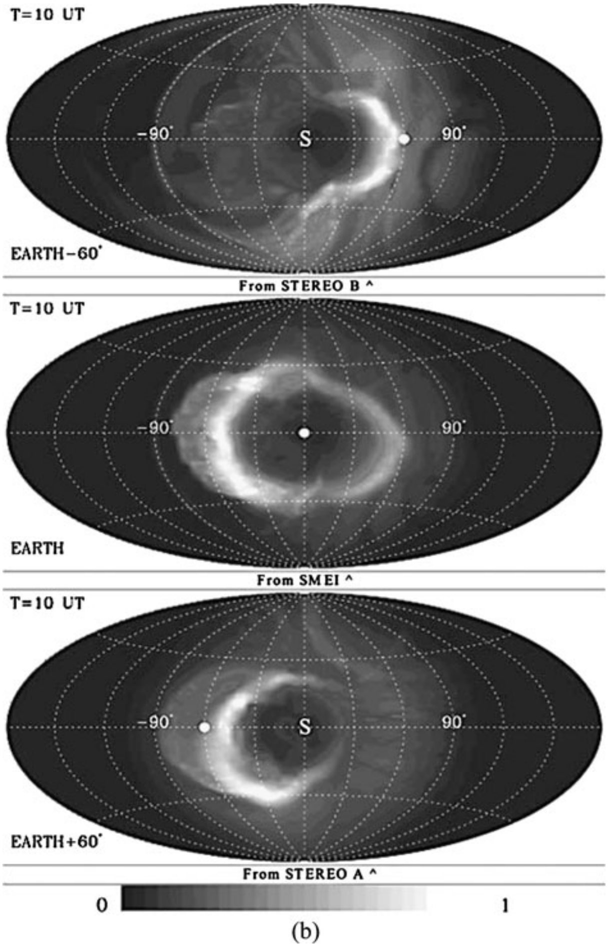
$$\varepsilon = VB^2 \sin^4(\theta/2)\iota^2$$

where

$V =$ the speed of the solar wind,
$B =$ the magnitude of the interplanetary magnetic field,
$\theta =$ the polar angle of the interplanetary magnetic field vector,
$\iota =$ a constant.

An intense geomagnetic storm results when both $V$ and $B$ are large and $\theta$ is 180°, namely, the vector is pointing southward. On the other hand, even if both $V$ and $B$ are large, there occurs no major storm if $\theta$ is 0°. For this reason, unless $\theta$ can be predicted, it is difficult to predict the storm intensity before the arrival of CMEs. Figure 35 shows $\varepsilon(= E)$, computed from the solar wind quantity $V$, $B$, and $\theta$, and the total magnetospheric dissipation rate $UT$

**Fig. 31** (*Continued*)

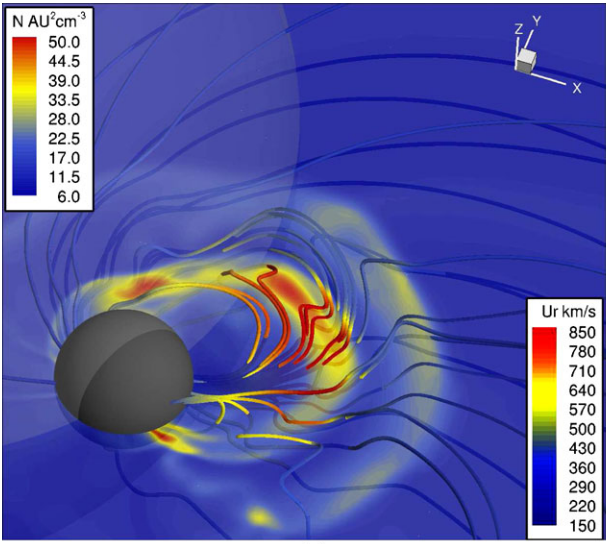



estimated from the two geomagnetic indices AE and Dst. The agreement between $\varepsilon(=E)$ and $UT$ is fairly good, despite the fact that both quantities resulted from independent sets of data. On the other hand, the correlation between the kinetic energy flux $K$ and $UT$ is poor, indicating the importance of $\theta$.

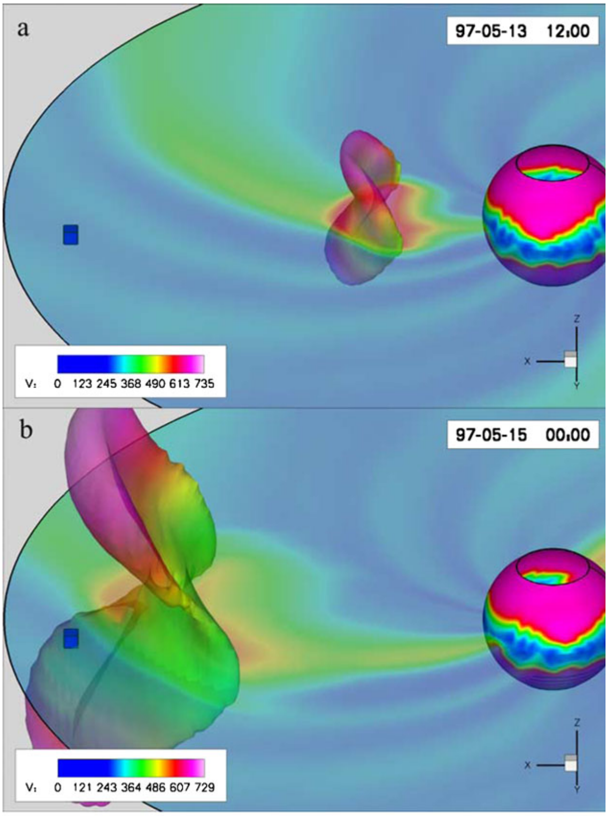
When solar physicists discuss geomagnetic storms, they often use the geomagnetic index Kp. It is hoped that they use physically more meaningful quantities, such as Dst, $\varepsilon$ or some quantities similar to it, instead the Kp index.

How the power $\varepsilon$ is dissipated in the magnetosphere to cause the main phase of the storms, magneospheric substorms and auroral substorms is still a matter of intense controversy, although there has been much progress in this field. When the power $\varepsilon$ is high, the magnetosphere appears to have internal disturbances, called magnetospheric substorms, with a lifetime of about three hours. During each substorm, oxygen ions ($O^+$) are injected into the inner magnetosphere to form the ring current around the Earth. Their diamagnetic (circular) motions are mainly responsible for the main phase, a decrease of the horizontal component in low latitudes, caused by the southward-oriented field near the Earth; Figure 36 shows the magnetic field produced by a model ring current, as well as the distribution of the currents.

**Fig. 32** (**a**) Simulated view of the CMEs at 16:00 UT on January 25, 2007. The black sphere radius is 17 solar radii (Lugas et al. 2009). (**b**) Simulated view of the advancing CME on May 13, 12:00 UT and 15:00 UT, 1997. The location of the Earth is shown by a *blue box* (Odstrcil et al. 2004). (**c**) Simulation of the expanding flux rope viewed from the Earth (Chen and Krall 2003)




(a)




(b)

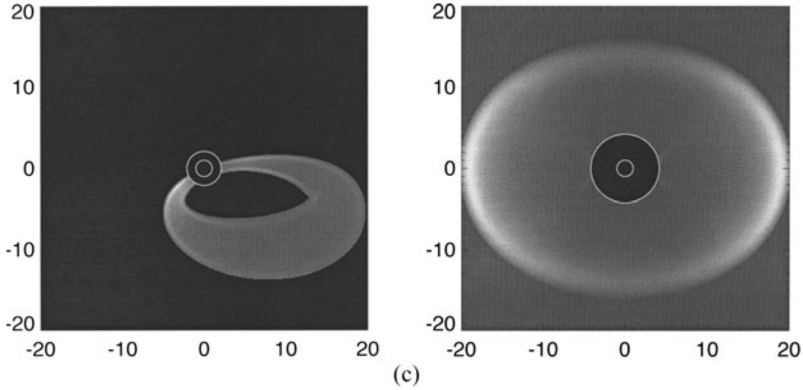



**Fig. 32** (*Continued*)

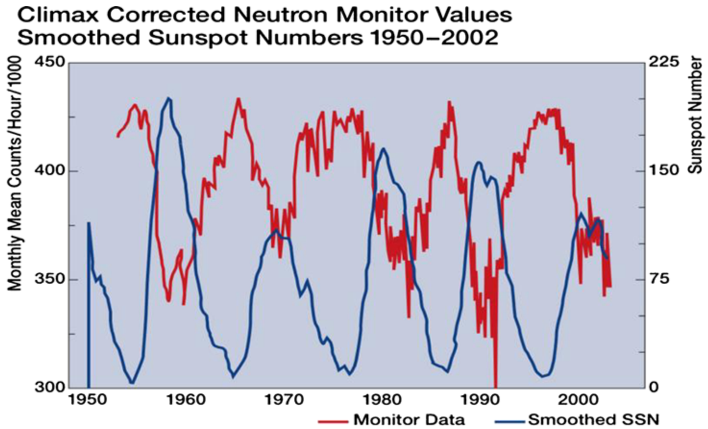



**Fig. 33** The sunspot cycle variations of cosmic-ray intensity; the *blue line* indicates the cosmic ray intensity, the *red line* the sunspot number (SPATIUM, International Space Institute, 2003)

## 8.2 Geomagnetic Storm Prediction

The success of identifying the expression of the power of the solar wind-magnetosphere dynamo $\varepsilon$ suggests that if we could predict the solar wind speed $V(t)$, the IMF magnitude $B(t)$ and the polar angle $\theta(t)$ as a function of time, it may be possible to predict the progress of geomagnetic activity *as a function of time*. For this purpose, a test was conducted for the storm of March 1974. Comparing the observed main phase decrease (Dst obs) and the predicted decrease (Dst pred), the result is reasonably successful, as shown in Fig. 37. It is clear that for the prediction to be successful, it is necessary to predict at least the quantities $V$, $B$, and $\theta$. There have recently been much effort toward this aim (Wu et al. 1999; Fry et al. 2003; McKenna-Lawlor et al. 2006; Smith et al. 2009 and others).

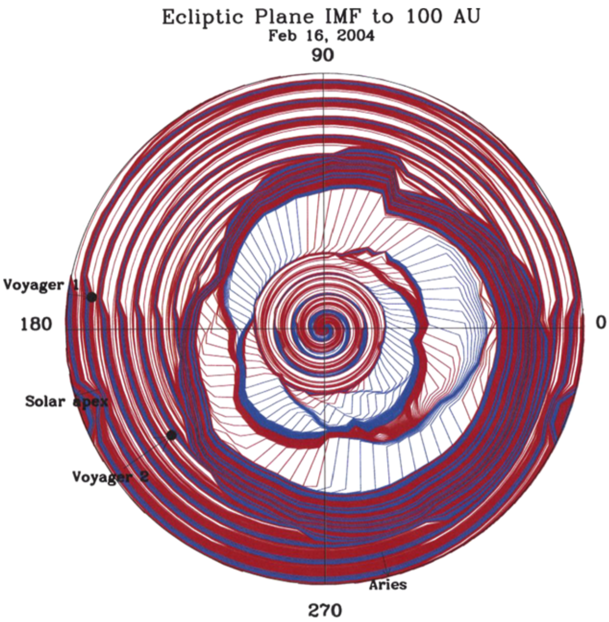



**Fig. 34** The simulated shock structure caused by a successive solar activity during the month of February 2004. The radius is 100 au; the location of Voyager 1 and 2 is indicated. After a series of intense solar activity, the quiet period resumed, as indicated by the regular spiral pattern in the inner heliosphere (Courtesy of W. Sun; see also Akasofu 2007)

## 9 Tentative Time Line of the Studies of Geomagnetic Storm-Producing Solar Plasma Flows

The time line of the development of geomagnetic storm-producing solar plasma flows is attempted here. This is a very difficult and delicate task without a much more comprehensive survey of the history of this particular science. In this paper, this task is mostly limited to up to about 1990 and also limited to the subject of geomagnetic storm-producing plasma flows, not the general solar-terrestrial relationship. The recent development is described in Sect. 6. The history will sorts out what to be chosen for the great advance during the last decade or so.

Time Line

1845: The first observation of solar flare by R.C. Carrigton.
1892: Lord Kelvin doubted the relationship between Carrington's observation and the geomagnetic storm which occurred day after, as well as the simultaneous Sqa(?).
1897: J.J. Thomson and G.P. Thomson suggested the newly discovered electrons are the cause of the aurora.
1904: E.W. Mounder confirmed that the Sun is the source of geomagnetic storms.
1908: K. Birleland made an extensive observation of the aurora and magnetic disturbances and also made the terrella experiment.
1911: C. Stormer begun auroral observations and calculate trajectories of electrons in the vicinity of the Earth.
1905: A. Shuster criticized Maunder's study.
1918: S. Chapman proposed his theory of geomagnetic storms.
1919: F.A. Lindemann criticized Chapman's theory and suggested that solar streams are plasma.

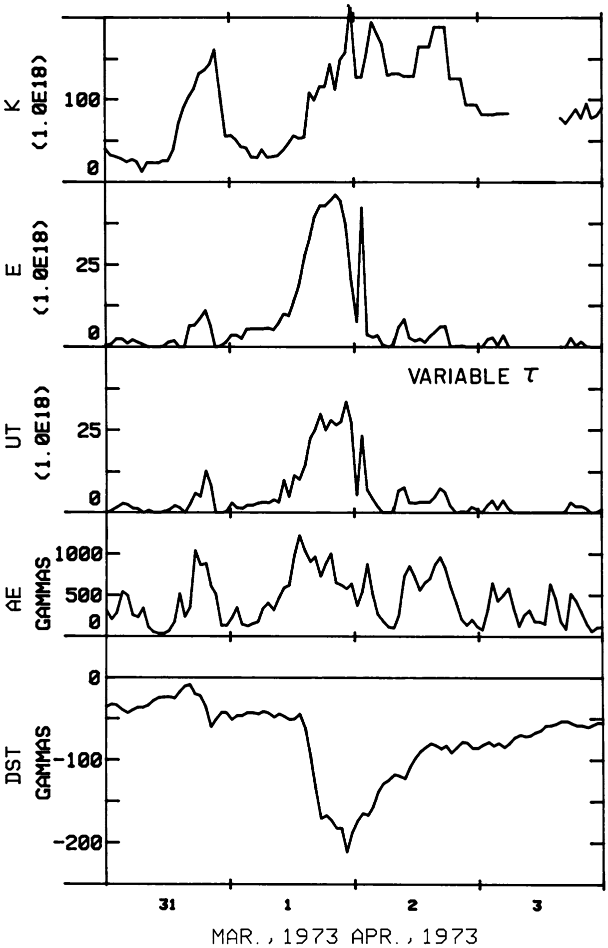



**Fig. 35** From the *top*, the kinetic energy flux, the $\varepsilon$ function estimated from the solar wind quantities, the total energy dissipation *UT* in the magnetosphere estimated from the two geomagnetic indices AE and Dst (Akasofu 1981)

1931: S. Chapman and V.C.A. Ferraro published their theory of the first phase of geomagnetic storms.

1932: J. Bartels confirmed Maunder's study.

1940: S. Chapman and J. Bartels published Geomagnetism.

1943: H.W. Newton found that the intensity of geomagnetic storms depends on the longitude of the responsible solar flares.

1949: F. Hoyle pointed out the importance of the interplanetary magnetic field in understanding the aurora and geomagnetic storms.

1950: H. Alfven proposed his theory of the aurora and geomagnetic storms.

1951: L. Biermann proposed that comet tails are affected by streams of particles from the Sun.

1955: H.W. Babcock and H.D. Babcock identified the UM-regions as a source of the solar streams.

1955: J.C. Pecker/W.O. Roberts, and D.E. Billings/W.O. Roberts proposed the cone of avoidance, effects of the solar magnetic field on solar streams.

1955: T. Gold proposed that the storm sudden commencement is produced by an interplaneart shock wave.

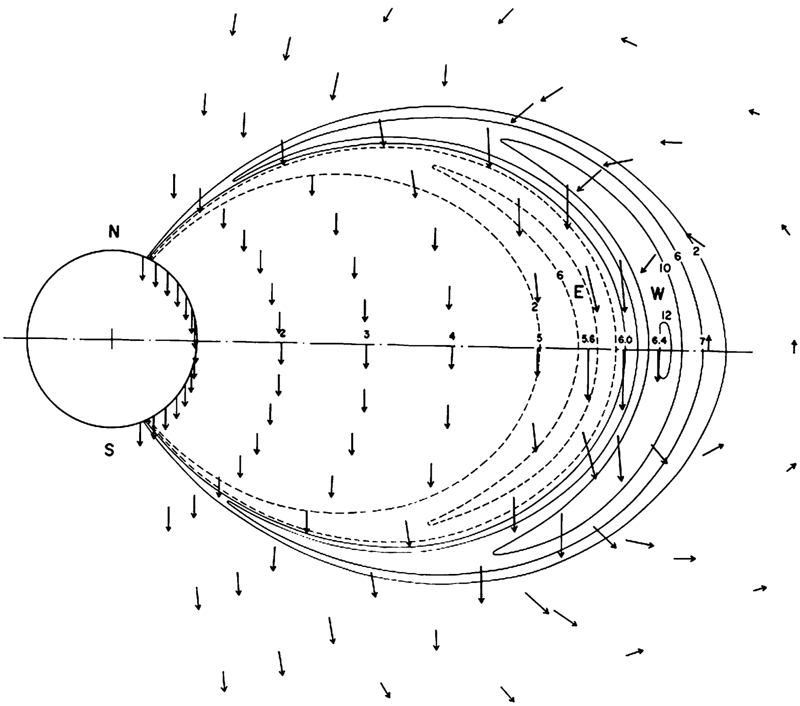



**Fig. 36** The distribution of magnetic vectors produced by a model of the ring current; W indicates the westward current and E the eastward current; since the W current is stronger than the E current, the ring current as a whole causes southward-oriented fields near the Earth (Akasofu and Chapman 1961)

1958: E.N. Parker published his theory of the solar wind.
1959: T. Gold proposed the term "magnetosphere".
1960: C.P. Sonett and his group observed the interplanetary magnetic field.
1961: J.W. Dungey published his theory of the interaction between the interplanetary magnetic field and the magnetosphere.
1963: S.-I. Akasofu and S. Chapman proposed "unknown" quantity in the solar wind which is responsible for the variety of the development of geomagnetic storms.
1964: N.F. Ness and his group mapped the shape of the magnetosphere and the shock front.
1965: J.M. Wilcox and N.F. Ness found the sector boundary structure of the interplanetary magnetic field.
1966: D.H. Fairfield and L.J. Cahill found that Akasofu/Chapman's unknown quantity is the southward component of the interplanetary magnetic field.
1970: J. Hirshberg and his group fond a helium-rich shell in the solar wind.
1972: Hundhausen suggested the structure of the driver gas.
1973: R. Tousey and others discovered the corora hole.
1973: J.T. Gosling and his group found an anomalously low temperature solar wind behind interplanetary shock wave.
1973: M. Schultz proposed the warpted current sheet for the interplanetary magnetic field.
1978: Tousey identified coronal mass ejections.
1979: Wu and his group made a time-dependent MHD simulation of solar disturbances.
1981: L. Burlaga found a spiral structure of magnetic field behind the interplanetary shock wave.

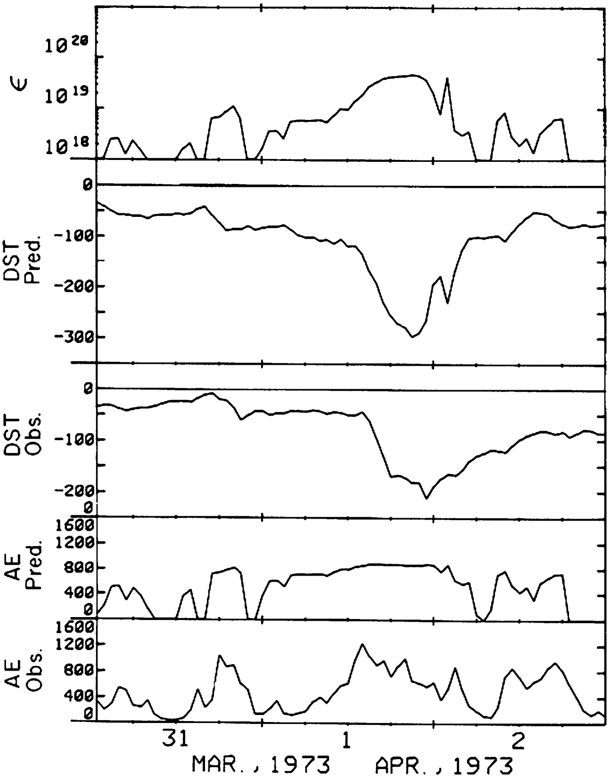



**Fig. 37** From the top, the $\varepsilon$ function, the predicted Dst index (Dst pred), the observed Dst index (Dst obs), the predicted AE index (AE pred), and the observed AE index (AE obs) (Akasofu 1981)

1982: R.A. Howard and his group found the structure of what we call now "coronal mass ejection".
1985: A. Hewish and his group observed interplanetary scintillation caused by shock waves.
1986: J.T. Gosling found bi-directional flows of electrons in coronal mass ejections.
1997: B.V. Jackson imaged solar plasma flows.
2003: D.J. McComas and his group obtained the latitudinal distribution of the solar wind speed.

## 10 Summary

It is clear that together with solar physics, studies of geomagnetic storms contributed greatly to the understanding of geomagnetic storm-producing solar plasma flows.

Looking back at the progress in the field during the last 100 years or so, we begin to understand the 27-day recurrent magnetic disturbances discovered by Maunder (1905). However, the nature of the source region of the streams, coronal holes, particularly the acceleration of the streams, needs further investigation.

The structure of intense storm-producing plasma flows has become increasingly clear in terms of coronal mass ejections (CMEs) and also of the $\varepsilon$ function. As late as the 1960s, it was thought that an increased solar wind pressure was all that was needed to produce geomagnetic storms. We know now that CMEs are associated with shock waves and magnetic clouds. CMEs may be like a polyhedron in some sense, and we have learned so far only a few surface elements. We should not suppose that we know now the whole polyhedron. Occasional observations of $He^+$ and H suggest that the chromospheric gas or filaments are a part of CMEs. Since solar flares are a very complex phenomenon (especially, magnetically), CMEs might take different shapes for individual flares.

There are a number of problems associated with (1) the quiet-time solar wind, (2) streams from corona holes and (3) CMEs, beside intrinsic problems on solar flares (or more properly solar storms Akasofu and Chapman 1972), magnetospheric substorms and geomagnetic storms. Some of the major problems from the point of view of a geophysicist are listed below.

(1) The quiet-time solar wind
   (a) What is the acceleration mechanism of the quiet-time solar wind? During the last part of the last sunspot cycle, the solar wind became very weak in association with the overall declining activities of the Sun. This must tell something about the mechanism of the acceleration of the solar wind particle.
   (b) Where is the source region on the Sun? Does it vary during the sunspot cycle?
   (c) What is the meridian view of the solar wind flow and the interplanetary magnetic field? We need an improved version of Fig. 15. How does it change during the sunspot cycle in association with the distribution of the magnetic fields on the photosphere?
(2) The streams from coronal holes
   (a) What is the acceleration mechanism of the streams?
   (b) From what part of corona hole do the streams flow out?
   (c) What is the 3D structure of the flow (3D version of Fig. 6a)? How does it vary during the sunspot cycle? These questions are important in predicting recurrent geomagnetic storms.
(3) The CMEs
   (a) What is the acceleration mechanism?
   (b) Because individual solar flares are different, the topology of CMEs may be different for different events, including bubbles, ropes or loops? Are some of them detached from the photosphere? Are some rooted in the photosphere?
   (c) Is there any way to infer the magnetic structure from the magnetic configuration around sunspot groups, filaments or from interplanetary observations? This knowledge is crucial in predicting how individual geomagnetic storms develop as a function of time.
   (d) What part of the solar atmosphere is included in CMEs? Are filaments in CMEs?

Common to all these issues (1), (2) and (3) is the acceleration mechanism of solar plasma. Alfven (1950) pointed out that the ratio of the Lorentz force/gravitational force can be as large as $10^5$ in the solar condition. It is unlikely that any thermal process can overcome the gravitational force. Furthermore, CMEs must plow through a slower quiet time solar wind. Alfven (1981, p. 74) suggested a plasma gun-like process, in which the Lorentz force $\boldsymbol{J} \times \boldsymbol{B}$ plays a crucial role in the ejection process. For example, Chen and Krall (2003) have an eruptive flux rope model for CMEs based on the Lorentz force. For the quiet-time solar wind and the streams, such a condition (namely, the presence of the Lorentz process) might occur as small-scale processes in large areas, while it will be a large-scale process in a limited area for CMEs. It is expected that the current of $10^{10}$ amperes or more is expected to flow around solar flares (cf. Akasofu 2011). It should be noted, however, that the assumption of force-free fields eliminates the very solution of this particular problem at the outset, just like the case of a study of the acceleration of auroral electrons using the standard MHD approach.

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