SOLAR ACTIVITY, CORONAL HOLES AND THEIR INFLUENCE

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Abstract

The pioneering observations of the Skylab instruments during the interval May 14, 1973—February 3, 1974 have brought into focus the solar feature of coronal holes and high speed streams. This unique mission enabled a continuous monitoring of solar evolution over a broad range of wavelengths, not possible by ground-based measurements. The solar polar coronal holes and the magnetic fields relating to the polar regions play a significant role in modulation processes in the off-the-ecliptic plane. In the past, in situ measurements have been essentially restricted to the ecliptic plane $\pm 7.5°$. The connection of coronal holes to the M-regions of Bartels, connected with the recurrent magnetic storms, has been realized.

This review deals with this new solar feature against the background of other features of solar activity which have been associated with phenomena involving solar terrestrial (planetary) relations. We are concerned with the role of coronal holes in modulation processes particularly connected with some of the cosmic ray intensity variations.

A summary of the essential characteristics of coronal holes and associated solar streams is also incorporated in order to enhance our understanding of the modulation processes.

INTRODUCTION:

It has long been realized that solar activity controls and modulates most phenomena studied in the interplanetary medium. There is general agreement that galactic cosmic rays stream into the solar system from beyond and are modulated by solar interaction. However, the intensity variations of cosmic rays, arising from a variety of causes, are super-imposed on one another to form a complex mosaic. The deciphering of this "resultant observation" and sorting out the various effects with specific association to particular solar feature(s) or parameter(s) has been progressing gradually. Thus the discovery of the new solar feature, namely coronal holes, has added yet another dimension to our understanding of cosmic ray variation. A basic question has been: which is the ideal solar parameter for correlative studies of phenomena involving solar terrestrial (planetary) relations?

SUNSPOT NUMBER AND CORONAL GREEN LINE 5303Å:

The readily available time series of sunspot number naturally has become the first choice. The inverse correlation between the annual means of sunspot number and cosmic ray intensity was discovered by Forbush (1954). Later investigations have adopted the intensity of the coronal green line 5303Å (for example, Sarabhai et al (1954)). The studies of Gnevyshev (1963, 1967 and references therein) and Balasubrahmanyan and Venkatesan (1968, 1970a, 1970b and references therein) have demonstrated that the two solar parameters are complementary to a certain extent; the choice depends largely perhaps, on whether one is investigating the electromagnetic or corpuscular aspects of solar influence. It is relevant to mention here that the 10.7 cm (2800 MHz) solar flux is yet another parameter which can be used for correlative studies, this however follows fairly closely the variation in sunspot number.

SOLAR WIND SPEED:

The Mariner 2 observations in 1962 confirmed the existence of the continuously flowing solar wind predicted by Parker (1958). Yet another parameter of solar activity, namely solar wind speed entered the field of correlative studies. The association between peaks in the values of Kp, the geomagnetic disturbance index and those in solar wind speed, persisting over 5 consecutive solar rotations, was pointed out by Snyder, Neugebauer and Rao (1963). This has also highlighted the existence of high speed stream or solar wind of abnormally high speed within the ever-present solar plasma and its recurrence. The subject matter of high speed streams will be considered again later.

The possible relationship between solar wind speed on one hand and geomagnetic activity and cosmic ray intensity variations on the other hand, have been of considerable interest to those involved in the studies of solar terrestrial relations. Using Mariner 2 data, Snyder et al (1963) have obtained the following empirical expression:

$$V\,(\text{km}/\text{sec}) \simeq (330 \pm 17) + (8.44 \pm 0.74)\, \Sigma\, K_p$$

Where V is the solar wind speed, Kp is the planetary geomagnetic index of activity and Σ indicates the daily sum of the 8 three-hourly values of the index. There exists, however, a considerable scatter in the data points. They have also reported a negative correlation between the daily means of solar wind speed and cosmic ray intensity over the interval August 29, 1962—January 3, 1973, but the correlation is not very strong.

Barichello (1978) has made a comparative study over the interval 1964-1976, of the time series of solar rotation means of sunspot number, spacecraft measurements of the speed of the solar wind plasma and cosmic ray intensity registered by the Sulphur Mountain Super-Neutron Monitor. It has been pointed out that the solar wind speed does not follow solar activity as represented by sunspot number in an obvious and simple manner, while the generally well-known inverse correlation between the variations in sunspot number and cosmic ray intensity still holds good.

This lack of an apparent connection between the 11-year cosmic ray variation and solar wind speed is in agreement with the studies of Mathews et al (1977) and Hedgecock et al (1972) using much smaller data sets available at that time. The possibility of a relationship on a short term basis in not ruled out by any of these studies. Furthermore it is important to realize that solar wind measurements are essentially restricted to the ecliptic plane, and this may have limitations.

The importance of observations in off-the-ecliptic plane has only been realized, of late. The nature of the physical processes in the solar polar regions is of considerable interest to those involved in studies of the physics of the solar system. At the present time, very little is known about how the solar wind and the magnetic fields originating from the polar regions contribute to the modulation processes operating in the interplanetary medium. Another feature that needs special consideration is the high speed solar wind streams and the role played by them in modulation processes.

BARTEL'S M-REGION:

Observational evidence has been accumulated for a long time that geomagnetic disturbances tend to recur with a periodicity of $\sim$ 27 days as viewed from the earth. Thus connection to the solar equatorial region and the solar control of geomagnetic variations was realized. The pioneering work of Bartels (1932) and Chapman and Bartels (1940) led to the interpretation of the geomagnetic disturbances in terms of long enduring solar plasma or ionized streams of matter originating from a localized source in the equatorial solar region. The recurring geomagnetic storms were particularly predominant during the decreasing phase of the sunspot cycle. Since no particular or specific features were identifiable, the regions were called M-regions standing for "Mystery regions." It has now been realised that these geomagnetic disturbances are associated with high speed solar streams. In other words, the picture of the ever-present general solar wind flow is modified with the additional feature of fast streams. The view is emerging and gaining strength that M-regions can be identified with coronal holes.

SOLAR WIND STREAMS:

Stream speed increases to a maximum in a day or two and falls back to the original value in $\sim$ 5-days. One can mention an increase from $\sim$ 300 km to 600 km during Mariner 2 period and a little less in later periods. The fluid interaction between the fast and slow speed flows in the solar wind should be borne in mind as this could introduce considerable variability in the general solar wind properties.

It is appropriate here to delineate a significant feature of the structure of solar wind stream. The interplanetary magnetic field, when averaged over relatively long periods of time, is observed to be directed into the well-known spiral pattern. Parker (1958) has pointed out that such a pattern is to be expected when the magnetic field is frozen within a plasma, expanding from a rotating source, say the sun. Furthermore, the magnetic field within is very well organized; thus one observes the field directed inwards (or outwards) at a time, for a few days and then changes in a short scale time. (For detailed discussion, refer to Wilcox (1968)).

The interplanetary sectors seem to be related to photospheric regions of weak magnetic fields and of the same predominant polarity as pointed out by Ness and Wilcox (1967) and Wilcox and Ness (1965). The figure on the cover page taken after Hundhausen (1978) indicates a phenomenological model relating the interplanetary stream structure and the large-scale coronal magnetic structure.

SKYLAB MISSION:

The observations of Skylab mission during the interval May 1973—February 1974, have significantly advanced solar physics by providing a continuous observation of the Sun over a wide wavelength band, not attainable by ground-based observations. The detailed study of the evolution of the Sun over this period by six experiments has resulted in a wealth of data relating to the new solar feature of coronal holes and to high speed solar streams, thus providing some new insights into the solar regime which governs and controls the interplanetary medium (for details, refer to Zirker (1977)).

CORONAL HOLES AND THEIR CHARACTERISTICS:

In recognizing the significant advance that has been made in our understanding of the solar feature of coronal holes and the associated high speed streams, it is appropriate to point out some of the other and earlier contributions. The list is by no means complete, but is only intended to serve as examples. The contributions of Waldmeier (1957, 1975) Reeves and Parkinson (1970), Vaiana et al (1973), Krieger et al (1973) Altschuler et al (1972) are some examples. (For further details, refer to Bohlin (1977)). In essence a reasonable picture of the characteristics of coronal holes existed even prior to skylab. It is also relevant to point out that coronal holes have been studied over a wide electromagnetic spectrum extending from X-rays to radio wavelengths. The following essentially summarizes the coronal hole features after Zirker (1977).

Coronal holes are large-scale regions of abnormally low density and temperature in the solar corona. The magnetic field lines are open in coronal holes, diverge in the inner corona and open out in interplanetary space. They encompass unipolar magnetic field essentially.

Coronal holes avoid regions of "high solar activity", and they are statistically associated with high speed solar wind streams.

As the name itself implies, the holes are essentially coronal phenomena. This can be easily seen by a study of the radiation from the transition zone and chromosphere. The holes are hardly identifiable from the chromospheric background.

Individual holes may cover an area as much as 1-5% of the solar disk; their life may last as little as one solar rotation or as much as 10 solar rotations and more. They occur at low latitudes as well as polar caps; connection between them was observed at least during Skylab period.

Coronal holes rotate relatively rigidly with a period of 27 days, with a pole to equator variation of $\sim 3\%$. The average picture over several solar rotations indicates growth and decay rate of coronal holes, approximating to Leighton's rate for the diffusion of photospheric magnetic fields by super granulation cells. But when we consider time period of one solar rotation, changes in coronal holes may occur abruptly and coherently over distances larger than the super granulation cell.

It is relevant to point out that ground-based observations of 10830Å line of He I reveal the presence and area of coronal hole. Study of the brightness of K-corona (white light) show that regions of weak emission correspond to coronal holes (Hansen et al. 1976). Thus ground based data which exist for a number of years can be used for studies relating to coronal holes.

CORONAL HOLES, SOLAR WIND STREAMS AND INTERPLANETARY SECTORS:

The inter-relationship amongst coronal holes, solar wind streams and inter-planetary sectors has been explored not merely for the Skylab period but for a much longer period, in view of the availability of a variety of complementary data. Hundhausen (1978) points out that the temporal development of individual holes, exhibiting the following sequence occurs without any drift in Carrington longitude, within 6-8 solar rotations: Appearance of small isolated hole at low helio latitudes, connection to polar region of same magnetic polarity and finally shrinking of the area of the hole and eventually disappearing. He also mentions about the tendency of the holes to occur in a regular pattern in solar or Carrington longitude, separated by $\sim 90^\circ$.

Hundhausen (1978) further summarizes the following results from a number of investigations.

a. If a large coronal hole is present near the helio equator, a fast solar wind stream is observed at the earth's orbit, with the magnetic polarity of the stream and hole being identical. This is inferred from the dominant polarity of the photospheric region beneath the hole, or from the polarity of the polar region connected to the hole.

b. Small coronal holes may not produce high speed streams.

c. Some solar wind streams occur even in the absence of near equatorial coronal holes as defined by observation of the low corona (X-ray, XUV wavelengths).

d. Large near-equatorial coronal holes are a sufficient but not a necessary condition for the existence of a high solar wind stream.

Therefore it is appropriate to raise the question whether there are different types of fast streams or whether fast streams can originate from different causes.

SOLAR POLAR REGIONS AND SOLAR WIND STREAMS:

We have already drawn attention to the fact that studies in the past have essentially been connected with modulation processes in the ecliptic plane and contributions from out-of-the ecliptic plane have not been assessed nor taken into account seriously. This picture has been changed significantly by Skylab observations.

Specifically, it has been pointed out by Hundhausen (1978) that there is evidence for the approach of the polar cap coronal hole to the ecliptic plane between solar rotation 1596 and 1598. This region has been suggested as the source of the magnetic storm associated with the so-called "monster stream" of the period (Bell and Noci 1976). The large polar influence on the solar wind in the ecliptic plane and the implication of an appreciable amount of North-South flow of the expanding solar plasma has also been pointed out by Hundhausen. In summary there is evidence for the emission of high speed solar wind from the solar polar regions, and that this can reach ecliptic plane, if the polar coronal hole stretches towards the helio-equator within $\approx$ 20-30°.

CORONAL HOLES AND FAST STREAMS:

From a compilation of data on all the coronal holes during the period, Hundhausen (1978) points out that $\sim$80-85% of available cases are associated with high speed streams. Looking from the other side, of the 34 prominent streams of high speed solar wind, 27 clearly reveal association to coronal holes of proper magnetic polarity, and 4 more seem to be associated with polar cap extensions lying just beyond $\pm$ 30° helio-latitude. In short, only 3 cases exist with no association with a coronal hole or polar extension. The point is further made by Hundhausen about the almost one to one association between coronal holes and fast streams during the Skylab period, and the observation of some large fast streams not associated with equatorial holes, is removed to a large extent by including solar polar cap extensions in the list of possible coronal sources.

CORONAL HOLES, FAST STREAMS AND INTERPLANETARY MAGNETIC SECTOR STRUCTURES:

Our particular interest in solar activity and its various manifestations arises from the effects these have on the interplanetary medium; the consequence would be seen in modulation processes involved in solar terrestrial (planetary) relations. Thus the evolution of solar coronal holes and fast streams are closely related to the changes in the interplanetary features.

The question has been asked, are interplanetary magnetic sectors and streams identical ? Hundhausen (1978) points out that the commonly held view that they are, is an oversimplification. He refers to the tendency of slow coronal hole drift to the East pointed out by Krieger (1977); the 27.1 day periodicity of recurrence of the high speed streams pointed out by Gosling et al (1976); and the 28.5 day recurrence period of related magentic sectors. He suggests that there is no discrepancy because of the small difference in the recurrence periods. While a given hole and fast stream of a certain polarity are fixed in a coordinate system of 27 day periodicity, the development of a new hole and stream of the same polarity to the east and subsequent decay and disappearance of the initial hole results in an eastward drift of the magnetic polarity pattern carried into interplanetary space by the streams. The eastward drift through one full solar rotation in an interval of $\sim$20 solar rotations implies a difference of $\sim$1.4 days.

Hundhausen (1978) rightly concludes that any model of the expanding corona should incorporate the new wealth of information on the coronal and solar wind structures that have energed as a consequence of the Skylab and other complementary studies. It is, appropriate to conclude this section by referring to his comment about the development of a very stable coronal structure in 1974 which resulted in a couple of recurrent geomagnetic disturbance sequences that continued for about two years with little change. He points out to the correlation of these storms with a stable two-sector two-stream interplanetary structure with large amplitude solar wind speed variations. The coronal sources for these streams were a pair of solar polar extensions of opposite polarity and large area. A singular and vital forward step has taken place in our thinking, namely, the recognition of the necessity to consider three-dimensional and large scale aspects of coronal and interplanetary structures.

Studies in the past have been concerned with measurements of solar wind speed essentially in the ecliptic plane ($\pm$ 7.5°). Radio scintillation data have given some indication about the need to consider features in off-the-ecliptic plane. But the Skylab observations for the first time have demonstrated the fact that important contributions from solar polar regions should be expected in modulation processes in the interplanetary medium.

CORONAL HOLES AND COSMIC RAY INTENSITY VARIATIONS:

There is general agreement among researchers that a simplistic view of long term correlation of average solar wind speed obtained from the ecliptic plane with cosmic ray intensity variations is no longer a meaningful approach. However, this does not necessarily mean that solar wind which sweeps the entire interplanetary medium has no influence. The solar streams and thus coronal holes may yet play a significant and dominant role in cosmic ray modulation.

Duggal and Pomerantz (1971, 1976) refer to modulation of cosmic ray intensity in the North and South pointing directions for interplanetary shock waves at large angles with respect to ecliptic plane (see also Mercer et al. 1971).

The study of Agrawal et al (1978) uses Skylab measures of solar polar coronal holes (Bohlin 1977) and demonstrate, that during non-disturbed periods, the North-South gradient of galactic cosmic rays as measured at 1 AU depends upon the difference in areas of the solar polar coronal holes. Higher intensity of cosmic ray fluxes are observed from the polar direction with the smaller coronal hole area. The existence of a large coronal hole over one polar cap relative to the other would inhibit the entry of galactic cosmic rays to the solar system from that direction because of some unspecified type of sweeping mechanism by the wind. In this study, Agrawal et al have used the data on the sizes of the solar polar coronal holes for five different time intervals using the Skylab measurements during the condition of solar minimum in 1973-1974. For galactic cosmic rays data, use has been made of the ground based neutron monitors at Thule, Greenland and McMurdo base, Antarctica. It is relevant to mention here the study of Nolte et al (1976) who have observed a relationship between area of hole, and the speed of the solar wind streams, in that the increase in area is accompanied by an increase in wind speed.

The results of Agrawal et al (1978) have been obtained over a short interval during the Skylab period. Further work has been done and the analysis carried out over a period of two years, using solar polar coronal structure as determined from ground-based K-coronal measurements which are available for long periods of time. Since regions of weak K-coronal white light emission have been shown to coincide with coronal holes, during Skylab period (Hansen et al 1976), studies relating to coronal holes can be carried out over long intervals of time. This study of Venkatesan et al (1979) confirms the study of Agrawal et al (1978).

The lack of a consistent correlation over a long-term period, between the average solar wind speed, measured essentially in the ecliptic plane and the cosmic ray intensity had been pointed out earlier. It is relevant to draw attention to studies such as that of Nolte et al (1976). For very large coronal holes or polar extensions within $\pm$ 30° helio-latitudes, the maximum solar wind speed approached 700-750 km/sec. But small young coronal holes and solar polar holes which do not reach even 50° helio-latitude, do not produce high speed streams; however, they affect the interplanetary magnetic field in the ecliptic. Thus small coronal holes may produce solar wind of their own dominant polarity, but with low solar wind speeds as measured at earth's orbit, and polar hole extensions may influence magnetic polarity in the ecliptic plane, even though, not close enough to the ecliptic, to impose their characteristic high speed stream flows upon it, as pointed out by Hundhausen et al (1976) and Wagner (1976). The discussion above, makes it possible to understand somewhat the lack of unique correlation between average solar wind speed and cosmic ray intensity.

CONCLUSION :

It is becoming quite clear that solar control from out-of-the ecliptic plane is an important aspect that has to be borne in mind, in connection with modulation mechanisms invoked to explain cosmic ray intensity variations in general and even in the ecliptic plane.

The solar polar satellite mission scheduled for passage over the solar minimum conditions in 1986 is expected to enhance our understanding of the solar control of the interplanetary medium.

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