INTERPLANETARY RESPONSE TO SOLAR LONG TIME-SCALE PHENOMENA

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In this paper, we briefly review the experimental knowledge gained in the recent years on the interplanetary response to solar long-time scale phenomena such as the coronal magnetic structure and its evolution. Observational evidence that solar wind flow in the outer corona comes from the unipolar diverging magnetic regions of the photosphere is discussed along with relations to coronal holes. High-speed solar wind streams observed within the boundary of interplanetary magnetic sectors are associated with these structures. Their boundaries appear as very narrow velocity shears.

The value of the maximum velocity increase is related to the amount of divergence of the field lines at the base of the corona which is less in large unipolar regions and causes the expansion to be faster according to theoretical models. Radial variations and solar cycle modulations of these structures are also presented.

1. INTRODUCTION

Sunspots are traditionally a marker for solar activity. Their variable number is used to keep track of the solar cycle. In order to understand the 11-year solar cycle effects on the relations between the Sun and the interplanetary medium, it is important to determine the magnetic structure of the base of the corona and its variations. Changes in the properties of the interplanetary medium result from these. This paper does not intend to describe all the long time scale variable phenomena in the interplanetary medium ; its goals are to review the periodic variations due to solar rotation and to present the changes which have been observed during the cycle of activity of about 11 years.

There are areas of the solar surface where the magnetic field lines are connected to the interplanetary medium. These open structures are surrounded by regions where the magnetic field has different polarities linked by closed loops of the magnetic field lines. In these areas where the magnetic field is open, the divergent geometry of the field lines acts on the coronal expansion of the solar wind. Pneuman and Kopp (1971)

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have shown that the expansion speed is greater where the divergence is less. When such regions pass in front of an observer the plasma flow which is detected is changed and temporal variations are observed with a 27-day period of recurrence if the lifetime of the source structure is greater than the time for one solar rotation. The size and the position of these areas of the corona evolve with time and general trends can be established during the solar cycle.

These long term variations occuring during a solar cycle have received increasing interest in recent years (see Nolte et al. 1978 and references therein). Progress has been made with identification of the coronal holes as those parts of the solar structure which act as sources of high-speed streams (Krieger et al. 1973). In this paper we intend to give a brief review of the experimental evidence gained in the past years concerning the evolution of the properties of the solar wind and of the interplanetary magnetic field during solar cycle 20 (1965-1976) and the beginning of the cycle 21.

2. RECURRENT HIGH SPEED SOLAR WIND STREAMS

2.1.Coronal holes

Coronal holes appear as dark areas on the white light photographs taken during solar eclipses and also on photographs made in soft X rays. Since they have been recognised as sources of interplanetary fast streams, these structures habe been the object of regular observations, summarized recently by Bohlin (1977) and Broussard et al. (1978). Several empirical properties can be deduced from observations (Zirker 1977). First the coronal holes are seen as regions where the intensity of the coronal emission is lower : dark areas on the white light photographs of the corona taken during total solar eclipse, or on the photographs of the corona taken in XUV and EUV (Broussard et al. 1977, Bohlin 1977). The simplest explanation of the general darkness of coronal holes is that the electron density is reduced and/or that temperature is lower.

Coronal holes are found in large unipolar magnetic regions. At the photospheric level the magnetic field intensity is weak in the coronal holes by comparison with surrounding areas (Vaiana et al. 1973, Bohlin 1977). At an altitude of about 2 R_S (solar radii) the magnetic field intensity of the coronal holes is of the order of 2-10 Gauss larger than in quiet background areas where it is of the order of one Gauss (Svalgaard et al. 1978). It is noted that coronal holes are quasi-permanent features of the poles of the Sun. Their polarities are constant through 11 years and reverse at the time of the maximum of the solar cycle. We are presently observing a positive polarity (away from the sun) in the northern hemisphere polar hole, (negative in the southern polar hole), and a reversal is expected around 1981, the forecast maximum year for solar cycle 21. Coronal holes which are present at lower, high, or mid-latitudes are often extensions of the polar caps. Lifetimes of coronal holes are found from one to more than 10 solar rotations (the average is about 5 solar rotations). In 1973-1974 a coronal hole was observed to last as long as 16 solar rotations. It is during the period of decreasing solar activity that the largest and the most stable coronal holes are observed. Another characteristic feature of coronal holes is their apparent rigid rotation rate with a 27.2 day synodic period. They are comparatively unaffected by the usual differential rotation rate of the surface of the Sun even when they extend from the polar cap through a large heliolatitude range across the equator (Timothy et al. 1975).

Extensive investigations in the past years have demonstrated clearly that coronal holes are the sources of most of the high-speed streams in the interplanetary medium ; notably solar wind high velocity flows are often observed to be recurrent during several solar rotations with only slight variations in amplitude and structure. Intercomparisons between coronal hole data, solar wind velocity, interplanetary magnetic field variations and geomagnetic activity enforce the idea of the relation between high-speed flows and coronal holes first presented by Krieger et al. (1973, 1974). However it is important to note that not all coronal holes are associated with fast streams in the interplanetary medium and that some long lived high-speed streams are not correlated with coronal holes. Nevertheless the latter high-speed streams seem to be associated with diverging unipolar coronal magnetic fields areas (Levine 1978, Burlaga et al. 1978).

2.2. High-speed streams

In the literature there are numerous examples illustrating the association between high-speed streams and coronal holes (Nolte and Roelof 1977, Burlaga et al. 1978 a, 1978 b, Levine 1978, Schwenn et al. 1978). Figure 1 is an illustrative example of the observation made at 1 AU by IMP 7 and IMP 8 during 1973. The velocity profile (upper panel) shows three high velocity streams. Each begins by a velocity increase which corresponds to an increase in the interplanetary magnetic field intensity (second panel from the top) measured by the HEOS 1 and HEOS 2 magnetometer. The magnetic polarity is also shown. The panel at the bottom is a map of coronal holes at the photospheric level during solar Carrington rotation 1607. A clear association can be seen between the central meridian passage of coronal holes and observations of high velocity streams when taking into account the delay time needed for the solar wind to reach 1 AU. Several characteristic features can be seen from this display.

2.2.1. High-speed solar wind streams are observed within a single magnetic sector. These come from a source position located within a unipolar magnetic region. Figure 2 of Gosling et al. (1976) shows the position of high-speed streams relative to interplanetary magnetic sectors measured during many successive solar rotations. Most of the high velocity streams are located inside unipolar magnetic sectors. Sometimes several streams can be seen in the same sector as shown in the right hand side of Figure 1, and they are related to different coronal holes of the same coronal unipolar magnetic region. Inside a

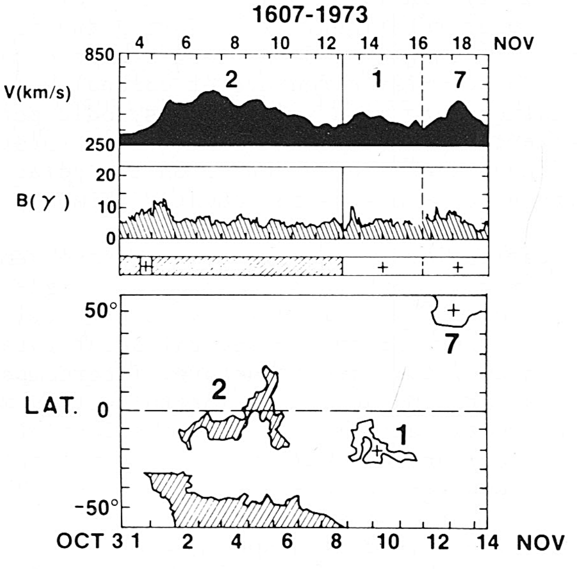

Figure 1. The top panel shows three interplanetary streams observed at 1 AU together with the magnetic field intensities and polarities in these streams. The bottom panel shows a map of the coronal holes from which the streams probably originated. The photospheric magnetic field polarities in the coronal holes agree with the polarities in streams at 1 AU. (from Burlaga et al. 1978a).

magnetic sector there is a tendency for the streams to be present near the leading edge of the sector and sometimes across this boundary due to the interaction of the fast flow with the slow ambient plasma during the corotation. Figure 2 indicates also that the high-speed streams have variable lifetimes. Some are present for only one solar rotation while others are recurrent during many solar rotations as from the end of 1973 through 1974.

2.2.2, Most of the high-speed solar wind streams are associated with equatorial or low latitude coronal holes. This has been established through studying the correspondence between the magnetic polarity inside high-speed streams and inside coronal holes deduced from magnetic observations of the Sun and also through comparing the longitudinal position of the sources of the streams with the position of the holes.

The first kind of association can be explained by the example of Figure 3 where observations made during solar roation 1609 are presented. We note that high-speed solar wind streams are well associated with low latitude or equatorial coronal holes. It remains to be explained why there is a negative polarity sector between streams n° 7 and n° 4 and why stream

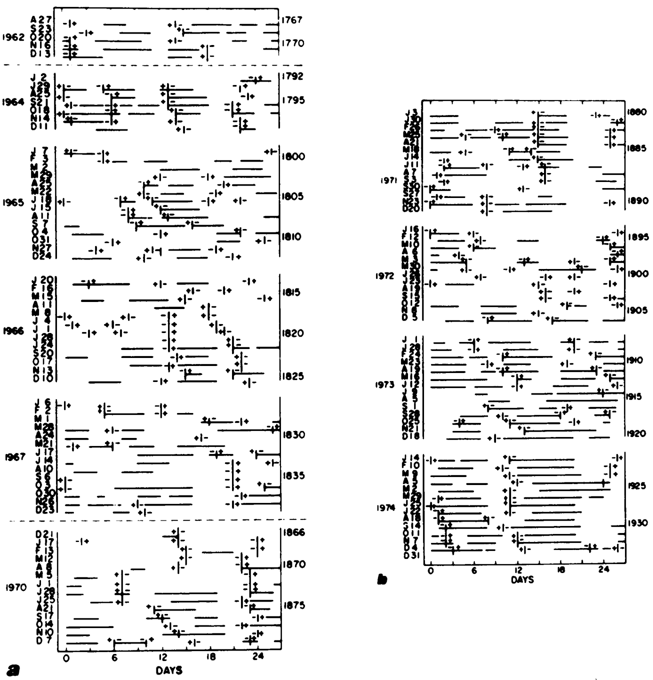

Figure 2. High-speed solar wind streams (horizontal bars) and interplanetary magnetic field sector boundaries (vertical lines) plotted according to 27-day Bartels rotations. Note that there are no reliable stream data for 1963, 1968, or 1969. The plus and minus refer to the field polarities on either side of the sector boundaries. The numbers on the right refer to the Bartels rotation numbers. Note that almost all streams are unipolar. Two series of recurrent streams dominate the late 1973 and 1974 period. (from Gosling <u>et al.</u> 1976)

n° 2* lasts for such a long time. Burlaga et al. (1978a) computed the magnetic field using the assumption that the field is force-free in this range of altitude and forcing the field lines to be radial at the outer boundary. The photospheric feet of the open field lines are mapped in Figure 4. For rotation 1609 several coronal holes are also present on this Figure along with areas which were not reported as coronal holes but with diverging open magnetic structures and whose polarities explain the observations in the interplanetary medium. For example a negative polarity area on the solar equator at a heliographic longitude of 320° can be correlated to the negative interplanetary sector observed between December 17 and 19. Also the negative polarity areas seen close to the solar equator and located between heliographic longitudes of 40° and 100° can explain the extension of the interplanetary magnetic sector after January 3. In order to be sure that this is not merely a fortuitous coincidence it is useful to locate the source of the high-speed streams near the base of the corona. A simple way to do this is to assume that

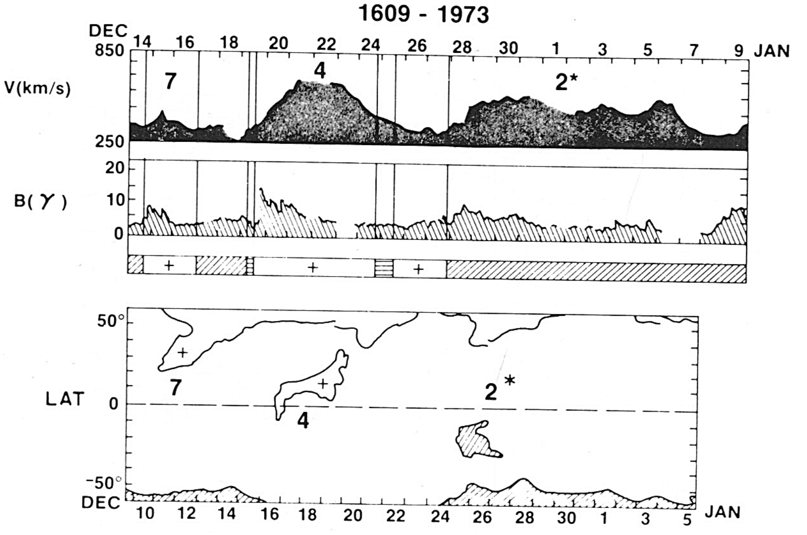

Figure 3. Interplanetary streams and magnetic fields for CR 1609 (from Burlaga et al. 1978a)

the plasma propagated radially from the Sun at the constant velocity observed at 1 AU. Figure 5 is from Nolte et al. (1976) who used this method for rotation 1609 (note that time is running from right to left). The first point of each day is indicated by a heavy dot and alternate days are indicated. It indicates that fast stream n° 7 is connected to a place at about 340° heliolongitude which corresponds to coronal hole n° 7. In the same way stream n° 4 is consequently correlated to thecoronal hole between longitudes 210° and 270°. Observation of a fast stream with a negative magnetic polarity during all of the remaining time of rotation 1609 can also be interpreted with less certainty as corresponding to coronal hole n° 2 and to negative polarity areas open to the interplanetary magnetic field as computed by Burlaga et al. (1978a). Thus it seems that cases which give rise to high-speed streams in the solar wind are more fundamentally related to an open magnetic field structure than to coronal holes. Thus at this time of the solar cycle the solar wind behavior around 1 AU has been shown to depend mainly on the equatorial and low latitude structure of the corona.

2.2.3, High-speed wind streams have very thin boundaries. In the preceeding discussion concerning the interplanetary magnetic polarity in relation to the associated coronal sources, it could be seen that several adjacent regions of the Sun were competing. During solar rotation 1608 a positive polarity zone was observed on December 9 and was no longer registered during rotation 1609. From one rotation to the next the positive area and also the negative area at 60° of heliolongitude were displaced southward by about 10° (Figure 4), the negative polarity area coming closer to the equator and the positive open structure decaying as suggested by the presence of a positive polarity coronal hole

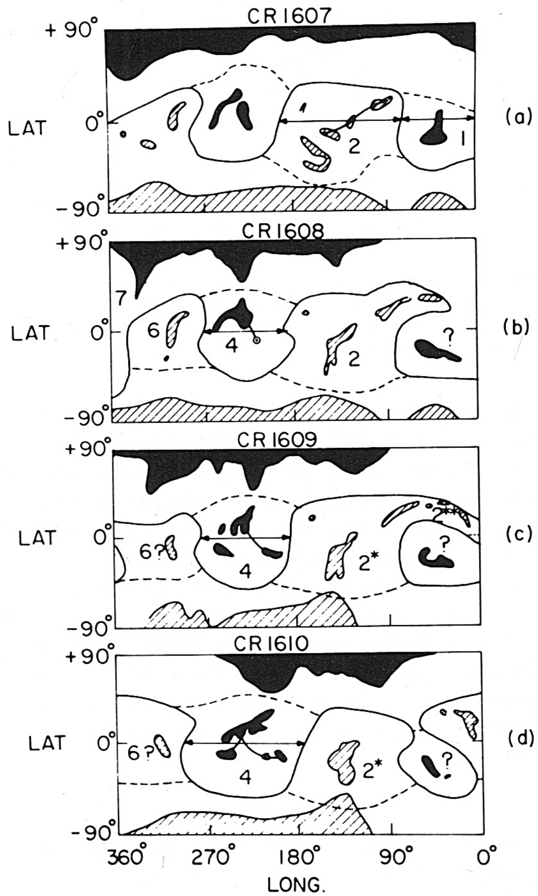

Figure 4. Map of the foot-prints of open magnetic field lines, their polarities (solid areas have positive polarity), the null lines (solid curves), and the saddle lines (dashed curves) for CR 1607-1610. (from Burlaga et al. 1978a)

at this place two rotations earlier. This could explain why an interplanetary flow with positive magnetic field became a flow with negative magnetic field during rotation 1609.

Schwenn et al. (1979) investigated the boundaries of the streams observed by HELIOS 1. In the front edge of a stream, the sharp velocity increase can be weakened by interacting with the slow ambient wind ; in certain circumstances it can begin to strengthen again when the spiral angle of magnetic field lines becomes larger and it can form a corotating shock structure. The boundary layers in front of a stream are thinner at 0.3 AU than at 1 AU and are more faithful images of the source boundaries. The angular extent of this limit is less than 5°.

The trailing edge of a fast stream does not interact with the slow ambient flow and thus it is possible to map back directly the source position using the extrapolated quasi-radial hypervelocity approximation (Nolte et al. 1973). Figure 6 from Nolte et al. (1977) gives a proof of

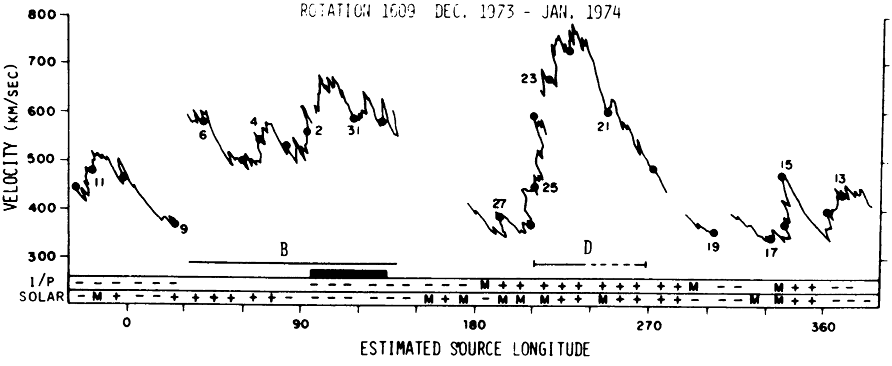

Figure 5. Hourly averages of solar wind velocity plotted against estimated source longitude for Carrington rotations 1609. The first point of each day is indicated by a heavy dot, and alternate days are indicated. At the bottom are indicated the 10° averages of interplanetary (I/P) and solar magnetic polarity. Above these polarity strips, near-equatorial coronal hole locations are indicated by the heavy bars, and the high-speed solar wind stream sources are labeled by letters. The estimated extent in longitude of the stream sources is marked by the horizontal lines, which are dashed during times of rapidly rising velocity. Short vertical lines mark the estimated edges of the sources whenever the solar wind data are complete (from Nolte et al. 1976)

the small width of the eastern boundary of the source. Apparent westward position changes indicated that interplanetary travel of the stream does not leave its structure unaffected. Taking into account interplanetary interaction effects and velocity related altitude change in the source position (Nolte et al. 1977), the angular width of the eastern boundary of the source is again of the order of 5°.

Using the observations made by IMP at 1 AU and by HELIOS near 0.3 AU at various heliocentric latitudes, Schwenn et al. (1978) have shown that the latitudinal boundary of high-speed wind streams was less than 10° wide. Thus with an average velocity increase of 300 km/s in streams, we are led to a velocity gradient of the order of 30 km/s/deg. Schwenn et al. (1979) related that in some cases, the observations made by HELIOS 1 and HELIOS 2 were completely different when these spacecraft were more than 5° apart in latitude. However, due to the longitude separation of the spacecraft, the measurements were not made simultaneously and thus temporal variations could have occured. Nevertheless in other circumstances when the latitudinal and longitudinal separation was very small, the observations suggest that the boundary could be very strongly inclined relative to the solar meridian plane.

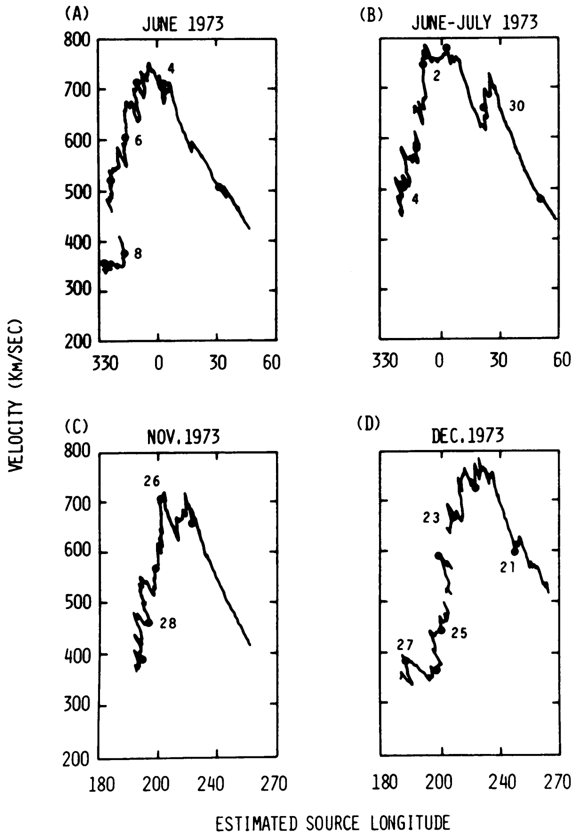

Figure 6. Same as Figure 5 for selected high-speed streams. Note the near vertical drop, or dwell in longitude, for two or three days at the eastern edge of each streams. (from Nolte et al. 1977)

2.2.4, In high-speed solar wind streams maximum velocity increases depend on the size of the associated coronal hole. Nolte et al. (1976) found a clear linear relation as shown on Figure 7. This relationship supports the theory that the divergence rate of the open magnetic field lines modulates the coronal expansion rate in the interplanetary medium. Magnetic field lines are expected to diverge more rapidly near the edges of coronal holes than in the central part. Thus the larger the hole, the more radial the magnetic field lines of the central part, or the less divergent the magnetic structure (Figure 8). Pneuman and Kopp (1971) and Pneuman (1973) investigated theoretically the flow resulting from coronal expansion in open and in closed magnetic configuration. They have shown that in open, divergent geometry the expansion rate is increased. Several theoretical models refined this approach (Kopp and Holzer 1976, Steinolfson and Tandberg-Hanssen 1977, Suess 1976, Pneuman 1976, Kopp and Orrall 1976). For a review see Suess (1979).

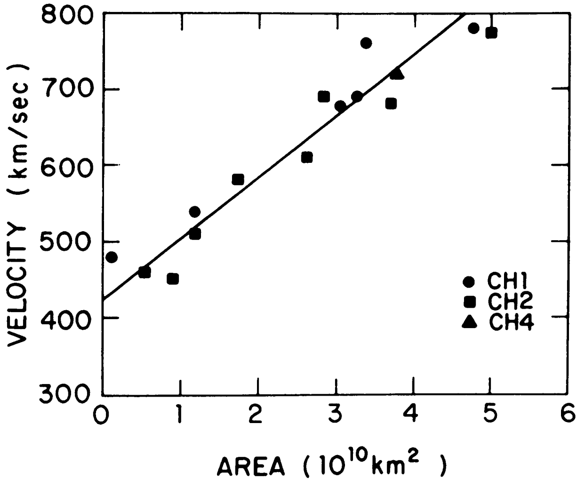

Figure 7. Maximum solar wind velocity vs. area of the associated coronal hole within 10° of the ecliptic plane. The least squares straight line is also shown. (from Nolte et al. 1976)

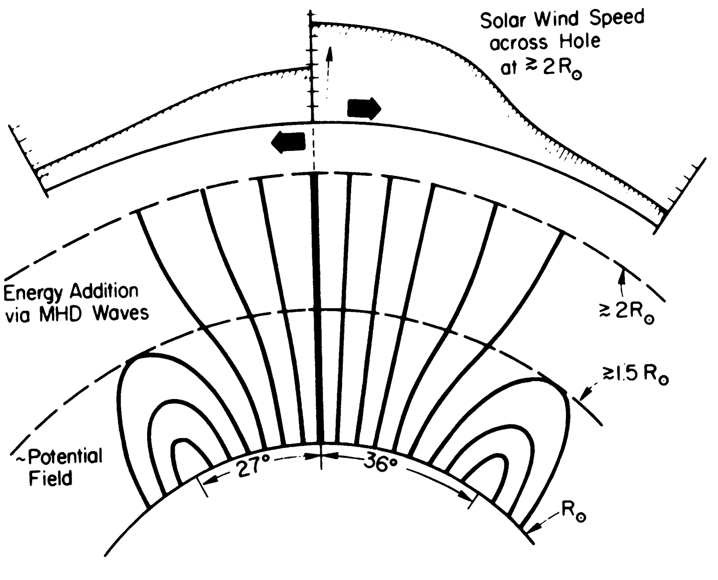

Figure 8. A hypothetical example of the influence of the size of coronal holes is illustrated on this schematic cross section of two coronal holes differing only in width. (from Suess,1979)

Generally the solar poles are extended coronal holes and it is logical to expect some higher velocity in the high-latitude solar wind. Statistical investigations done using interplanetary scintillation measurements of radio sources allow a determination to be made of the latitudinal gradient of the solar wind speed which was found to be 2.1 km/s/deg. (Coles and Rickett 1976). This value of the latitudinal gradient could be the effect of the diverging structure of the solar polar magnetic field. The divergence of flow tubes takes place in the base of the corona up to an altitude of about 3 R_s (Munro and Jackson 1977). In the case of a polar coronal hole observed in June-July 1973, this divergence is such that it could be deduced that 8 % of the total solar surface of the northern hemisphere was the source of plasma for about 60 % of the flow at an altitude of 3 R_s in the same hemisphere.

During March 1975 HELIOS reached perihelion at 0.31 AU and registered a fast stream with a longitudinal extent of about 30°. The associated coronal hole was identified as an equatorward extension of the southern polar coronal hole. Its longitudinal extent at the latitude of the spacecraft was not more than 10°. Thus the flow diverged by a factor of 3 between the solar surface and 0.31 AU (Burlaga et al. 1978b). This value is of the same order as the one which was established directly by Munro and Jackson (1977) : 2.9 between the solar surface and 5 R_s. Bohlin (1976) estimated that 15 % to 20 % of the solar surface was occupied by coronal holes during 1973-1974 and Bame et al. (1977) proposed the hypothesis that all the solar wind came from them. Following the same idea, several authors suggest that the basic state of the solar wind is the one observed in high velocity flows.

2.3. Radial variation

A large amount of data were obtained from interplanetary spacecraft between 0.3 AU and 15 AU so that it is possible to determine the characteristic behavior of fast streams with increasing distance from the Sun. The radial evolution of high speed wind streams has been described by Collard and Wolfe (1974), Gosling et al. (1976), Hundhausen and Gosling (1976), and others ; they showed that the interplanetary medium acts like a low pass filter. The rapid fluctuations are smoothed and large scale gradients are strengthened and finally give the sawtooth like velocity profile of the solar wind in terms of temporal evolution. Due to solar rotation, the flow undergoes an asymetrical evolution. The leading edge interacts with the slower and denser plasma. Starting near the Sun, the high pressure in the stream tends to widen the range of longitudes in which the velocity increase takes place. Then, because of the strong convergence of the fast and slow streams, the velocity and density gradients increase again and can result in the formation of a forward front shock and of a reverse shock. The momentum transfer through the interface reduces the velocity increase further from the Sun (Gosling et al. 1978).

Figure 9 gives an example of observations of a fast stream in two positions : at PIONEER 11 at 1.5 AU and at PIONEER 10 at 4.4 AU (Smith and Wolfe, 1977). The first spacecraft registered a velocity increase of

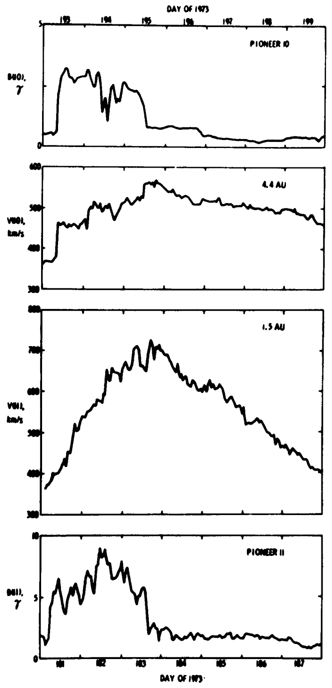

Figure 9. Evolution of a high speed stream between Pioneer 11 and Pioneer 10. The two upper panels show the field and velocity at Pioneer 10, B (10) and V (10), and the two lower panels show V (11) and B (11) corresponding to the same stream at Pioneer 11.

350 km/s within 2 1/2 days during which the magnetic field maintained an enhanced value characterizing the interaction region. During the same period (June-July 1973) IMP 7 and IMP 8 were radially aligned with PIONEER 11 and show that at 1 AU the velocity profile is steeper in the leading part with a twofold increase (Intriligator 1977). The velocity at 1 AU reaches about 800 km/s, slightly higher than the value of 760 km/s observed at PIONEER 11. Furthermore this higher value was observed for a longer time at 1 AU. This high speed solar wind stream is related to an equatorial coronal hole seen during Carrington rotation 1602 (Bohlin and Sheeley 1978). This coronal hole is located between longitudes 5° and 25° and the resulting fast stream at 1 AU is observed between longitudes -23° and 45° (stream B on figure 6) which shows again the divergence of the flow tube between the Sun and 1 AU. Applying the constant velocity radial propagation assumption to the data of PIONEER 10 at 4.4 AU it is found that the longitudinal width of the source of the stream is of about 70°. This value is the same order of magnitude as the one found from IMP data so it is concluded that the divergence takes place close to the Sun

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before 1 AU and that the flow expands spherically further out in the ecliptic plane. Following its propagation to 4.4 AU, where it was observed by PIONEER 10, this stream undergoes important modifications. First the velocity increase takes place in several abrupt steps and secondly the maximum velocity seen in the stream at 4.4 AU is much weaker (∿ 560 km/s). It is clear that a forward shock front appeared at the leading edge of the stream between 1.5 AU and 4.4 AU. Smith and Wolfe (1977) interpret this fact by suggesting that after they are formed, the shocks tend to mask the positive velocity gradients and eventually to eliminate the original large velocity difference associated with a stream. The interaction region here again is indicated by the high value of the observed magnetic field and probably ends as a discontinuity, which could be a reverse shock. This would tend to erode the velocity peak in the stream and then to propagate through the decreasing velocity portion. At larger radial distances a sawtooth like velocity profile develops. Another example is given on Figure 10 which shows the evolution of some high speed streams between 1 AU (IMP 7 and IMP 8) and 11 AU to 15 AU (PIONEER 10) (Collard, 1979) ; global characteristics of velocity profiles are observed to persist as far out as 12 AU, but they are much more attenuated at large heliocentric distances. The velocity fluctuations are smoothed and the average velocity in the stream is of the same order at large distances as at 1 AU but the standard deviation of the velocity histogram is much less at a larger radial position. (Collard 1979). Several discontinuities are then likely to appear as a result of the possible interaction between shocks. VOYAGER spacecraft will provide more details about the behavior of the solar wind at large radial distances.

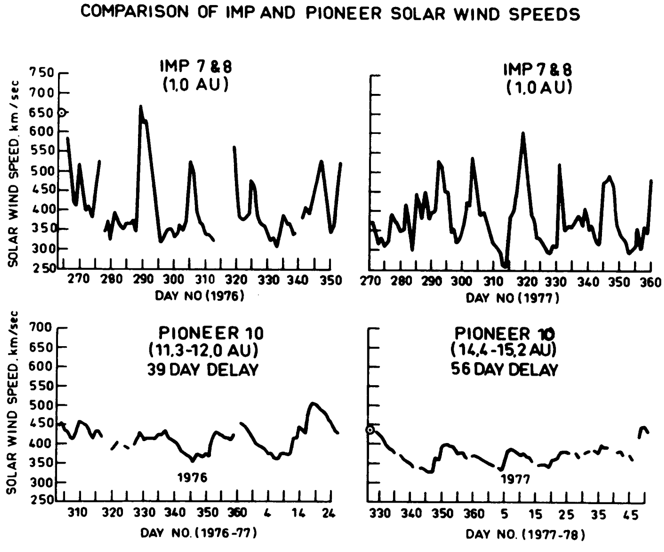

Figure 10. Comparisons of IMP and PIONEER solar wind speed measurements at the beginning solar cycle 21 (courtesy of Collard, ARC NASA, 1979)

3. SOLAR CYCLE VARIATION

Measurements of the solar wind registered since the sixties cover the entire solar cycle 20 and the beginning of cycle 21. Broussard et al. (1978) summarized the evolution of coronal holes during a solar cycle. In particular, they observed that during minimum solar activity, there were large polar coronal holes and that their area was decreasing with increasing solar activity. During the increase of activity, small sized polar coronal holes are seen to grow high latitude extensions toward the polar side of the sunspot belts. When the polar coronal holes have almost completely vanished during solar maximum, coronal holes can be observed north (south) of the northern (southern) sunspot belt and also at the equator between them. They have relatively short lifetimes. During the decaying phase of the solar cycle, equatorial holes tend to join the higher latitude ones giving birth to a stable disruption of the sunspot belts, and polar coronal holes appear again.

Comparing this evolution with that of the high speed streams, one concludes that small low latitude coronal holes are related to relatively narrow fast streams with velocities not more than 600 km/s (Bame et al. 1976) while large coronal holes even at mid latitudes give rise to extended streams with velocities greater than 700 km/s. Thus the long time scale changes of the corona modulates the solar wind behavior at 1 AU (Zirker 1977, Sheeley and Harvey, 1978, Sheeley et al. 1976)

3.1. Solar wind variations

Several authors investigated the long term variations of solar wind parameters at 1 AU. Hirshberg (1969) suggested that solar wind velocity should increase with increasing solar activity. Analyses made by Gosling et al. (1971), Wolfe (1972), Diodato et al. (1974) and Gosling et al. (1976) failed to ascertain any clear tendency when yearly averaged values were used. Between 1962 and 1974 these average values are from 398 km/s (in 1965) to 521 km/s (in 1974). There is a well defined maximum in 1968 (473 km/s) corresponding to the solar maximum but observations made at the end of solar cycle 20 do not show any velocity decrease. On the other hand Gosling et al. (1977) noticed that when compared to previous cycles, solar cycle 20 shows an unusual behavior in its decaying phase. Looking at the fast streams, Intriligator (1977) argued that the maximum value observed in 1968 (Figure 11) is sufficient proof of the relation-ship between the solar wind velocity and the solar cycle evolution.

From interplanetary radio-source scintillations, Rickett and Coles (1979) found that the latitudinal velocity gradient decreases when the maximum of the solar cycle is approaching ; this is in good accordance with the decrease of the size of the polar holes. Nolte et al. (1977) noticed that in 1976, the variations of the solar wind velocity were very similar to those in 1965 during the previous solar minimum. Diodato et al. (1974) gave evidence of a variation of the plasma density which decreases by 40 % between minimum and maximum solar activity and this was observed whatever velocity range was considered. This density variation was related to the latitudinal effect suggested by Hundhausen et al. (1971). During the minimum of solar activity the zones where the magnetic field is divergent are mainly located at the poles so that the flow of plasma converges into the equatorial plane of the sun at large distance. Thus at this time and in this plane there flows a slow and dense plasma whereas during the maximum of solar activity the flow probably comes from small coronal holes or narrow areas of divergent magnetic field at low latitudes and close to the equator. No clear temperature variations with solar activity were observed in the last solar cycle (Diodato et al. 1974). Feldman et al. (1978) have investigated the variation of the relative abundance of α particles and have shown that between 1971 and 1977 the relative abundance changed from 5 % to 3 % in the slow stream while it stayed at a constant value of about 5 % in the fast streams. Ogilvie and Hirshberg (1974) examined the observations between 1962 and

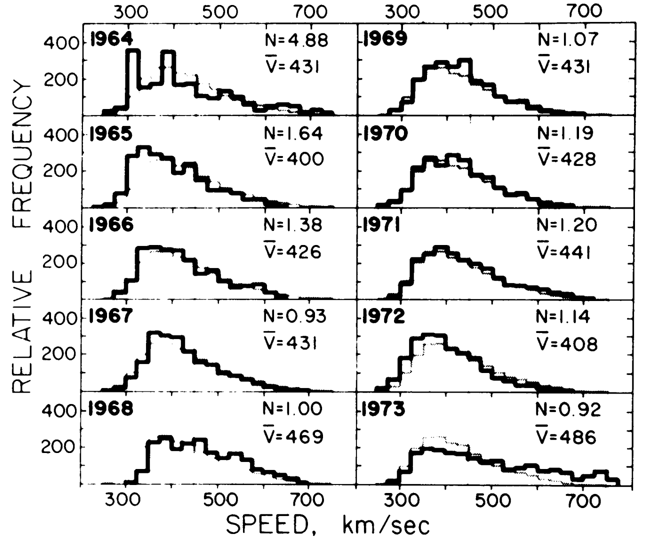

Figure 11. The dark lines indicate relative frequency of occurence of the solar wind streaming speed in intervals of 25 km/sec. for each year from 1964 through 1973. The light lines indicate the frequency histogram of the speed for the entire (parent) population composed of all the data from mid 1964 through 1973. The histograms have been normalized (there is the same area under each histogram) as indicated by the N's in the figure. The yearly average solar wind speeds are shown by the $\overline{V}$s. (from Intriligator 1977)

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1972 and found a variation of the relative abundance from 3-4 % at the time of minimum activity to more than 5 % at time of maximum activity, although with large error bars (about 1 %). These authors have also shown that this variation could not be attributed either to a variation of the solar wind expansion or to a variation of the number of transient phenomena in the corona.

3.2. Magnetic field variations

The interplanetary magnetic field was also measured during the period from 1964 to 1974 by several spacecraft. King (1976) and Mariani et al. (1975) conclude that the magnetic field intensity does not show any long term variations during this period of time. However King (1976) noticed that the magnitude and the azimuthal component of the positive magnetic fields went through a variation different from that of the negative fields. Siscoe et al. (1978) revealed that the histogram of occurence of B_z (normal to the ecliptic plane) changed with the solar cycle phase. The mean value of $|B_z|$ is always 0 but the mean value of the absolute value of B_z is larger during the time of the maximum of solar activity. Figure 12 shows the variation of $|B_z|$, of the related standard deviation and of the inverse of the slope of the corresponding histogram and reveals two peaks on each side of the time of maximum solar activity. Siscoe et al. (1978) associated these peaks with those of the 5303 Å coronal emission and with those of the production rate of energetic solar flares. The larger value of B_z during the time of high solar activity can be interpreted as a result of the complex magnetic structure during this period. Svalgaard et al. (1974) have shown how the general dipolar magnetic field during the minimum of solar activity gives a better arranged appearance to the interplanetary medium. During the growth phase of solar cycle 20 the solar north pole was a south magnetic pole and when the Earth reached its maximum heliographic latitude, more negative polarity magnetic fields were observed than when the Earth was south of the ecliptic plane (Figure 13). Then after 1970 when the magnetic polarities of the sun were reversed, the inverse was observed. In 1968, 1969, and the first part of 1970 there was no clear dependence between the number of days of observed negative polarity and the heliographic latitude of the Earth as expected from the complex structure of the solar fields.

These observations suggest that during the maximum of the solar activity, the interplanetary magnetic field is irregular and this explains why there is a minimum in the flux of cosmic rays at that time (Winkler and Bedijn, 1976). The irregular structure of the interplanetary magnetic field during the sunspot maximum increases the number of scattering centers for the energetic particles and, more importantly, the magnetic field lines in the heliosphere are likely to be more tightly and more strongly closed near the sunspot maximum making it more difficult for the cosmic rays to penetrate deep into the inner heliosphere (Yoshimura, 1977).

A delay of more than one year was observed between the sunspot

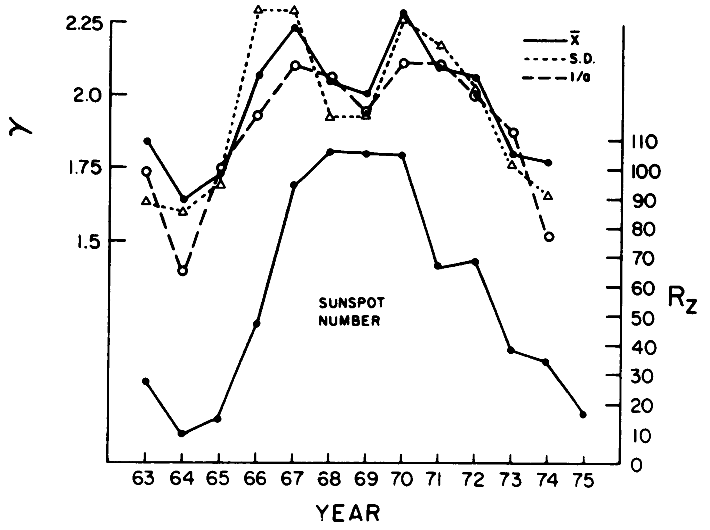

Figure 12. The top data field shows the yearly determined values of $\bar{x}$ ≡ average B_z, S.D. ≡ the associated standard deviation, and 1/a, the slope parameter which is defined in the text. The bottom data field shows the yearly averaged sunspot number, R_z. (From Siscoe et al. 1978).

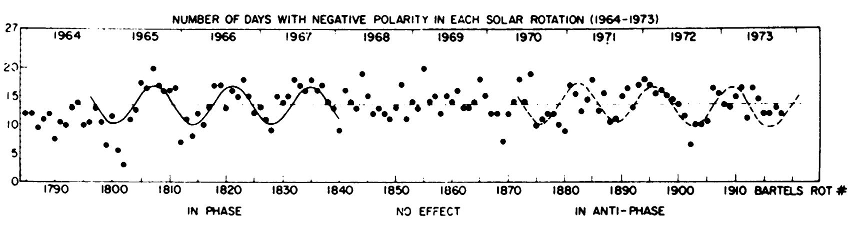

Figure 13. Number of days with negative polarity observed in the inferred interplanetary magnetic field for each Bartels 27-day rotation since 1964. Before sunspot maximum the amount of negative polarity observed varies in phase with the helio-graphic latitude of the Earth, but after maximum the two variations are out of phase (from Svalgaard et al. 1974).

minimum and the maximum of the flux of cosmic rays (Forbush, 1954) and indicates that the heliopause could be as far away as 100 to 200 AU. This estimate is done by considering that the solar wind carries the image of the coronal magnetic structure and consequently that the properties change at the heliopause late after the coronal modifications (Yoshimura, 1977).

4. CONCLUSION

In the light of these results the origin of the so called "quiet" solar wind remains to be explained, and it can be questioned how likely it is that the "quiet" solar wind represents the fundamental regime of coronal expansion. Nevertheless the fast streams which seem to be the normal regime of expansion have velocities (∿ 800 km/s) that cannot be reproduced by theoretical models, since the latter do not give velocities larger than 500 km/s. The role of the magnetic field divergence seems to be predominant but additional processes should occur at an important rate, probably through Alfven wave dissipation.

The solar cycle associated variations of the solar wind are not established with certitude yet due to the particular aspect of solar cycle 20 and also because data have not been collected for more than one and one half solar cycles. In the future, continuous observations of the interplanetary medium and further investigations of the measurements should make it clear if there is a strong relationship between the mean solar wind velocity and the solar cycle phase. Other questions remain unsolved which could be answered by extended programs of investigations. Among these are the question of the life history of coronal holes, the problem of the detailed behavior of the plasma processes involved between 2 R_S and 5 R_S, the problem of the flow over the solar poles and its variations. The last point will certainly become clearer after 1986 when the solar polar mission spacecraft pass over the solar poles at time of minimum solar activity.

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DISCUSSION

Bird: You presented a slide showing a velocity profile across a coronal hole, demonstrating that the solar wind speed peaks near the center of the hole where the magnetic field divergence was less than near the boundaries. It is not true, however, that the degree of magnetic field divergence affects only the radial rate of increase in velocity and not its asymptotic value?

D'Uston: This picture intended to show two open diverging coronal magnetic structures, the way the divergence of the field lines is smaller in the center of larger coronal holes and that observed velocity increases are larger there. It does not presume theoretical meanings; it is a schematic example of what is observed.

Suess: (Comment) I would like to add to the speaker's reply to the question from M. Bird regarding slide #8. The slide shows a Figure I prepared to show the well known empirical relationship between coronal hole size and solar wind speed at 1 AU, and also that there are empirical and model results which suggest that the energy supplied to the solar wind flow in the coronal hole depends somehow on the magnetic field strength and direction. This is not the same as saying the field divergence effects the solar wind speed at 1 AU directly - it does not, as Bird just stated.

Schatten: Your slide showing the small coronal holes and their relation to interplanetary sector structure appears to show that there are no "solar sectors", but the interplanetary structures arise from coronal holes. Do you agree? Also, sometimes small holes give rise to large sectors. Why?

D'Uston: Interplanetary sectors are connected to Unipolar Magnetic Regions of the Sun's surface. Coronal holes are embedded in them, thus there is no difference between the polarity of the high speed streams and that of the UMR from which it comes. I mentioned open diverging magnetic structures of the corona seem much more fundamental in giving birth to high speed streams. There are observations of interplanetary sectors without fast streams. Such interplanetary magnetic fields are carried out from UMR of the Sun by solar wind and this shows that not all the solar wind comes from coronal holes. It can be seen that small coronal holes in large UMR and the related magnetic sector is large.