SECTOR-STRUCTURED INTERPLANETARY MAGNETIC FIELD ASSOCIATED WITH THE FAST PLASMA STREAMS IN 1985–1996

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Abstract. An analysis of 373 well-defined high-speed solar-wind streams observed at 1 AU during the years 1985 –1996 is outlined. The distribution of the occurrence of these streams as a function of Bartels rotation days using the dominant polarity of the interplanetary magnetic field (IMF) associated with the referred fast streams shows that a four-sector pattern for the positive IMF polarity and a two-sector pattern for the negative IMF polarity are the dominant features in the investigated period. The high-speed streams seem to occur at preferred Bartels days: positive polarity streams are most frequent near Bartels days 5 and 18, while negative polarity streams are most frequent in days 14 and 23. Moreover, the corotating streams with positive IMF polarity prefer to occur in days 5 and 18 of the Bartels rotation period, whereas flare-generated streams with negative IMF polarity occur in days 14 and 23. The observed distribution of Bartels days is probably related to the distribution of the solar sources of high-speed solar wind streams as the solar wind carries with it the photospheric magnetic polarity of the solar source region. In addition, the distribution of the streams reveals a similar behaviour during the ascending and the declining phase of the last solar cycle (22nd) in contrast to the previous one where it has an opposite appearance. Determined differences in the characteristics of the sector structured IMF associated with the fast streams of the last cycle with the previous one (21st) and some similarities with the alternate solar cycle (20th) seem to be attributed to the 22-year magnetic cycle and to the polarity reversals of the polar magnetic field of the Sun. As the magnetic sectors are due to multiple crossings of the solar equatorial plane by a large-scale, warped heliospheric current sheet, it is suggested that the two-sector pattern arises from a tilted solar magnetic dipole component and the more commonly observed four-sector pattern from a quadrupole component of the solar interplanetary magnetic field.

1. Introduction

As the solar wind plasma expands radially outward from the solar corona, it carries with it the frozen-in interplanetary magnetic field, which is organised in large-scale sectors. Thus one observes the field directed inwards (negative sector) or outwards (positive sector) from the Sun for a few days and then the direction changes in a short time scale. This sector structure of the interplanetary magnetic field (IMF) was first discovered by Wilcox and Ness (1965) and as it was observed by near-Earth spacecraft, it generally consists of two or four sectors within a 27-day Bartels solar rotation period. Nowadays this structure is described in terms of a warped heliospheric current sheet (HCS) separating heliohemispheres of opposite magnetic polarity (see for instance, Hoeksema, Wilcox, and Scherrer, 1982; Hoeksema,

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1989). Hundhausen (1977), as well as Thomas and Smith (1981), described the HCS in terms of a tilted dipole model. However, the role of higher-order solar magnetic multiples cannot be neglected in the interpretation of the HCS structure during a solar cycle (Saito and Swinson, 1986). The dominant polarity effect of the IMF (Rosenberg and Coleman, 1969) is described by a model in which the HCS is represented by a simple sinusoidal curve, symmetric about the heliographic equator (Svalgaard and Wilcox, 1976) or shifted northward or southward parallel to the heliographic equator during periods of low solar activity, like sunspot minimum (Moussas and Tritakis, 1982). Girish and Prabhakaran (1988) noted that the presence of a magnetic quadrupole, in addition to a magnetic dipole in the heliomagnetic field, shapes the HCS geometry and the resulting IMF variations near Earth. The reversal of the sign of the dominant IMF polarity during a solar rotation period depends on the relative phases of the dipole and quadrupole components in the solar magnetic field.

As it is known, the HCS intersections with the Earth's orbit on the ecliptic plane, which have been detected as abrupt changes of the IMF direction by 180°, have been referred to as sector boundaries. These structures often lie ahead of fast solar wind streams that usually exhibit the dominant magnetic polarity of the coronal holes from where they originate. The large polar coronal holes tend to have the polarity of the hemisphere where they were born and this determines the polarity of their outgoing solar streams. This explains the dependence of the sheet configuration on the position of the coronal holes, as well as its asymmetric latitudinal structure, e.g. four sectors can be observed per solar rotation in northern latitudes in contradiction with two observed sectors in southern ones. The fast solar-wind streams arise because their very large velocity creates a subpressure, which gives rise to a large-scale deflection of the HCS towards the corresponding solar pole (Drillia and Moussas, 1996). A possible relation between the shape of the boundary and the coronal hole positions has been verified (Burlaga, Lemaitre, and Turner, 1977).

On the other hand, several studies have shown that the fast solar wind streams tend to recur in a nearly stationary 27-day pattern. An examination of their occurrence reveals that the distribution of streams as a function of Bartels rotation days is non-random and streams of different sector polarity occur at different Bartels days. Lindblad (1981) carried out an analysis of 346 high-speed solar wind streams observed at 1 AU during 1964–1975 and showed that a two-sector structure was the dominant feature of the interplanetary magnetic field associated with the high-speed solar-wind streams. In particular the corotating streams occurred most frequently near Bartels day 17 for negative polarity of IMF and near day 4 for positive polarity. For the non-recurrent flare associated streams the occurrence distribution did not show any defined peak. Lindblad explained these observations in terms of a tilted dipole model of the solar-interplanetary field with the tilt being different for the two epochs 1964–1970 and 1971–1975.

Later on Rangarajan and Mavromichalaki (1989) studied the solar wind streams as a function of Bartels rotation days for the period 1972–1984 for different categories of IMF polarity in order to provide a comparison with the earlier epoch. This study was based on a reference catalogue of well-defined high-speed streams for the period 1972–1984 published by Mavromichalaki, Vassilaki, and Marmatsouri (1988). They showed that the peak-to-valley modulation at the occurrence of high-speed streams during the solar cycle 21 was not so strong as it was during the solar cycle 20. They noted also that the occurrence pattern of the corotating and the flare generated streams reveals a clear phase opposition for the two polarities (negative and positive), while in the combined list of streams linked with sector boundary passage a phase opposition in occurrence pattern between $-/+$ and $+/-$ passages is also discernible.

Furthermore, Tritakis and Mavromichalaki (1992) analyzing 38 cases of sector boundary passages of the heliospheric current sheet by the earth observed by the ISEE-3 spacecraft have shown that sector boundaries in some cases occur preferentially at certain Bartels rotation days of the Sun although their distribution within the solar rotation at the maximum of the solar cycle 21 is quite different than those in the maxima of the cycles Nos. 18, 19, 20. This disagreement probably implies some kind of longitudinal relocation of the heliospheric current sheet induced by the differential rotation of the solar surface and the reorganisation of the solar activity that has been determined to take place at the end of each 22-year solar cycle.

In this contribution, the tendency of the high-speed solar wind streams to occur at preferred Bartels days and the interplanetary magnetic field sector structure during 1985–1996 is investigated using a catalogue of high-speed streams (Mavromichalaki and Vassilaki, 1998). The occurrence of high-speed solar wind streams in the Bartels rotation days has been computed in an identical fashion as was done by Lindblad (1981) and Rangarajan and Mavromichalaki (1989) for the corotating streams and the flare-generated plasma streams. For each type of streams, the distribution is further subdivided into two categories depending upon the IMF polarity. A comparison with observations for the earlier cycles 20 and 21 gives evidence for a different behaviour in the two phases of the even and odd solar cycles (premax and postmax periods).

Moreover, some interesting results are also obtained from further investigation of the stream occurrence during shorter time intervals. As a four-sector structure as well as a two-sector structure is observed in some cases, a tilted dipole model with the contribution of a quadrupole one is proposed to explain this pattern of the solar–interplanetary magnetic field.

2. Data Presentation

Recently, Mavromichalaki and Vassilaki (1998) prepared a catalogue with the series of well defined fast plasma streams observed near Earth during the period 1985–1996, as a continuation of the previous one (Mavromichalaki, Vassilaki, and Marmatsouri, 1988). This stream identification covers Bartels rotations from 2069 to 2231 (i.e., 162 Bartels rotations). Each stream observation was listed separately, regardless of whether or not it was a member of a recurrent series. The database for this study is the interplanetary plasma/magnetic field data compilation made available by the NSSDC/WDC-A for rockets and satellites (NASA/GSFC-Greenbelt). The new updated catalogue, apart from the main characteristics of the solar wind streams, contains as the previous one the dominant polarity of the interplanetary magnetic field for the duration of the stream and also provides cases where a sector boundary crossing ($+/-$ or $-/+$) was embedded in the solar wind streams. This is useful for the study of the distribution of the solar wind streams as a function of Bartels rotation days for the different categories. This distribution is non-random and streams of different sector polarity occur at different Bartels days.

In order to be investigated the tendency of the fast solar wind streams to occur at preferred Bartels days, the number of well defined high-speed plasma streams recorded at 1 AU during 1985–1996 as a function of Bartels day rotation is computed and plotted in the right panels of Figure 1. Separate curves for streams (together corotating and flare-generated) located in positive and negative interplanetary magnetic field sectors are shown. The IMF polarity is normally the same during the lifetime of a high-speed stream. In cases where a mixed polarity was observed the most frequent polarity was chosen. A regular pattern in the occurrence rate of high-speed plasma streams is shown in this figure. A clear phase opposition for the two polarities is observable as well as a strong peak to valley modulation of the occurrence rate is noted. The two curves of opposite IMF polarity seem to exhibit two peaks in a Bartels rotation period. The preferred days in Bartels rotation are the days 5 and 18 for positive polarity and days 14 and 23 for streams with negative polarity. Lindblad (1981) showed that the high-speed streams occurred also at preferred Bartels days during the period 1964–1975, where positive polarity streams were most frequent near Bartels day 4 and negative polarity streams were most frequent near Bartels day 17.

The occurrence rate of high-speed streams taken from the catalogue of Mavromichalaki, Vassilaki and Marmatsouri (1988) within the Bartels rotation days for the 1975–1984 years is also presented in Figure 1. It is apparent that there isn't any defined peak in the total number of corotating and flare generated streams for the positive as well as for the negative polarity of the IMF associated with these streams. This is a consequence from the weak peak-to-valley modulation of the streams during this time interval, unless a phase opposition between the positive and negative IMF polarity is observable.

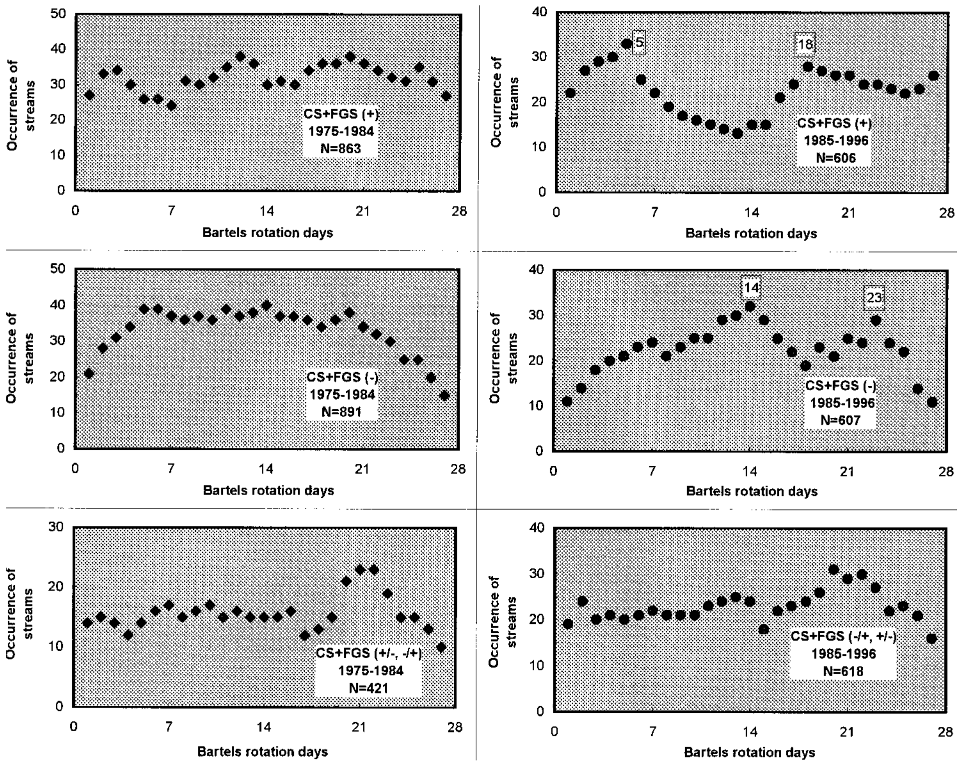

Figure 1. Occurrence number of the combined list of the corotating (CS) and flare-generated streams (FGS) within a Bartels 27-day rotation for positive and negative IMF polarity for the 1975–1984 and 1985–1996 years (upper and middle panels). The number of corotating and flare-generated streams associated with sector boundary crossings are also presented for the two cycles (lower panels).

The catalogue of high-speed streams includes a classification of the streams into the two classical categories: corotating (CS) and flare-generated streams (FGS) according to their possible sources. The corotating streams are emitted by coronal holes and are associated with simple decreases of cosmic ray intensity recorded at ground based stations, whereas the flare-generated streams seem to be associated with strong active regions, i.e., coronal mass ejections (CMEs) associated with chromospheric flares (Iucci *et al.*, 1979; Mavromichalaki, Vassilaki, and Marmatsouri, 1988; Landi *et al.*, 1998). The occurrence distributions of both classes of streams as a function of Bartels rotation days are reported in Figure 2. It is evident that the distribution of flare-generated streams (upper and middle right panels), differs from that of the regular or recurrent streams (upper and middle left panels). We add that in the total of 373 individual high-speed streams which are reported during the 1985–1996 data set, a total of 287 (77%) corotating streams and a total of 86 (23%) flare-generated streams are found. Obviously, the number of corotating streams is much greater than the number of flare-generated streams during the current solar cycle (Mavromichalaki and Vassilaki, 1998). The distribution of

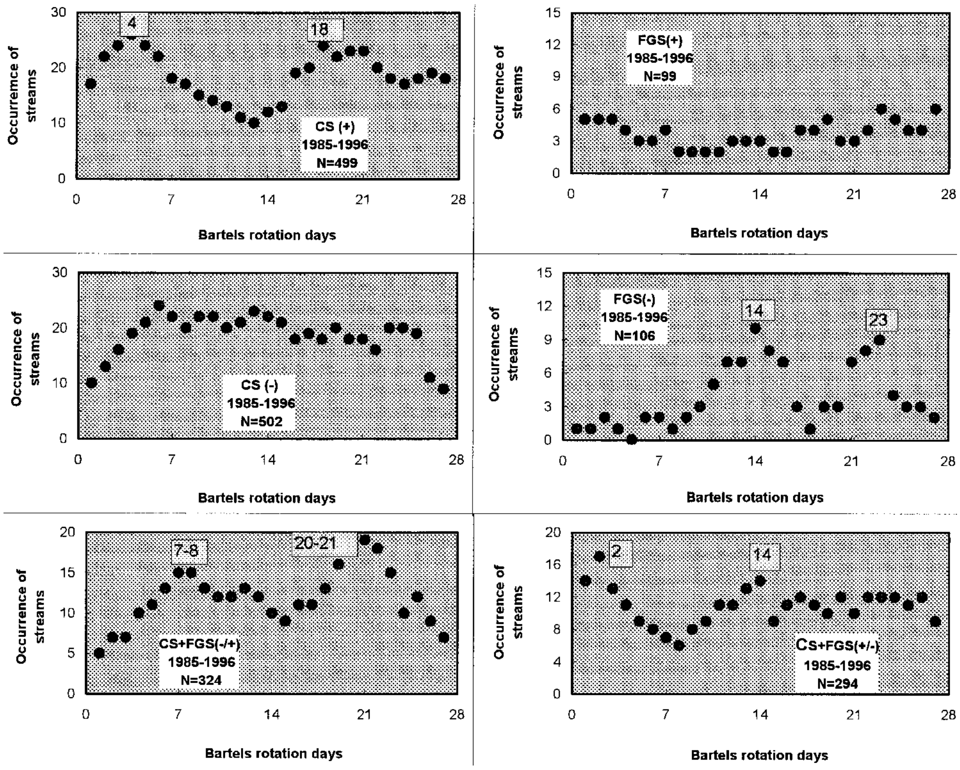

Figure 2. Occurrence number of the high-speed solar wind streams for the years 1985–1996 as a function of days in Bartels rotation. CS indicates corotating streams, FGS indicates flare-generated streams, (+) and (−) indicate IMF directed away and toward the Sun respectively. The distributions of the combined list of the corotating and flare-generated streams for the two types of boundary passages are also presented.

corotating streams (left side of Figure 2) is dominant and the number of flare-generated streams (right side of Figure 2) is small. We notice here that in the considered catalogue of fast solar wind streams, we have not take into account the cases of high-speed solar streams which have no determined IMF polarity because of data gaps. These cases, which are mainly related to corotating streams, are only a percentage of 8% of the total number of the streams which can not influence the reliability of the obtained results.

The analysis shows that a four-sector structure was the dominant feature of the interplanetary magnetic field associated with the corotating streams located in IMF of dominant positive polarity peaking at Bartels days 4 and 18. The distribution of high-speed corotating streams located in negative polarity sectors doesn't show any defined peak, but they present a 27-day variation peaking at the middle of the Bartels rotation period. On the contrary, the distribution of flare-generated streams with negative IMF polarity (right side of the same figure) presents two peaks in Bartels days 14 and 23, while there is a preference of these streams located in positive polarity sectors to occur at the edges of the Bartels period. This finding is partially consistent with the earlier result of Rangarajan and Mavromichalaki (1989), where well defined preferred days for streams associated with flares were near day 10 for positive polarity and near days 3 and 23 for negative polarity. The question is if solar flares responsible for these streams occurred on a preferred Bartels day or the associated active regions were so long-lived and active that a high-speed stream could be repeatedly observed.

An important feature of Figure 2 is that a strong peak-to-valley modulation of the occurrence rate of the corotating streams in the last cycle is outlined, which is in contrast with the previous solar cycle 21, but identical with the strong modulation of the cycle 20 (factor 7). This could be related to the fact that the 21st cycle was characterized by a higher activity than the other ones and thus both the number of flare-generated streams and their duration were large (Mavromichalaki and Vassilaki, 1998).

As the number of cases of fast streams associated with sector boundary crossings was far less, we combined together the corotating and flare-generated streams. The distributions of the two types of sector boundaries are shown in Figure 2 (lower panels). A phase opposition in occurrence pattern between $(-/+)$ and $(+/-)$ boundaries is discernible. There is also some preference of the sector boundaries to occur at certain days of the Bartels rotation. Actually the highest peaks of the $(-/+)$ boundary cases occur during the 7–8th and the 20–21st Bartels days whereas most of the $(+/-)$ boundaries prefer the 2nd and the 14th Bartels days. The above observation means that a four-sector structure is observable when both cases of sector boundaries are considered. This distribution pattern is similar with that found in the previous cycle (Rangarajan and Mavromichalaki, 1989), but it is not possible to compare it with the one for cycle 20 as the corresponding list of the streams does not include this category. The most striking feature resulting from the present analysis is the phase opposition noticed in the occurrence of the corotating streams located in opposite IMF sector polarity, which is not so clear in the occurrence of the flare-generated streams. This opposition is better observable in the two types of sector boundaries (lower panels of Figure 2). A similar phase opposition was reported in the previous cycles 20 and 21 by Lindblad (1981) and Rangarajan and Mavromichalaki (1989).

Anyway, we can say that the four-sector structure is a persistent feature over the last solar cycle (No. 22). As a verification to our main result a four-sector structure could also be obtained from the following simple calculation: since the time of observations (1985–1996) consists of 162 Bartels rotations, where there were at least 618 sector boundary passages where a corotating or a flare-generated stream occurred, we have on average $618/162 \approx 4$ sector boundaries per rotation. This result confirms that during this solar cycle a four-sector pattern predominates. Nevertheless, if polarity changes during high-speed streams exhibit such features it may be possible to infer the nature of the warp in heliospheric current sheet and

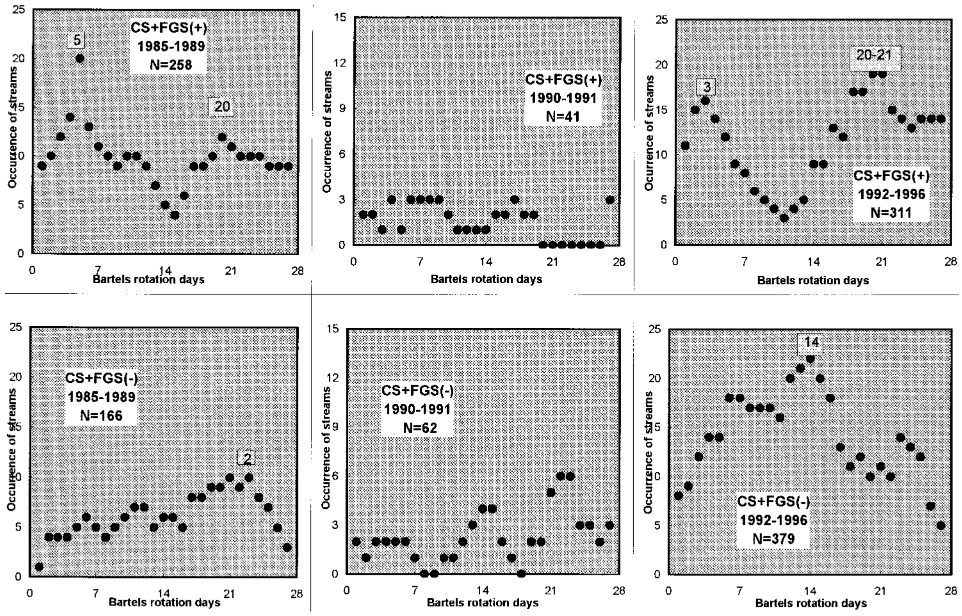

Figure 3. Number of days within a Bartels rotation during which a high-speed stream is observed at Earth for the periods 1985–1989 (premax), 1990–1991 (field polarity changeover) and 1992–1996 (postmax).

suggest suitable schematic models to account for the observed features during the solar cycles.

3. Sector-Structured IMF in Solar Cycles

The persistence of two or four-sector structure of the interplanetary magnetic field was investigated by dividing the 1985–1996 data sample into smaller groups.

In a first study the number of observed corotating high-speed streams as a function of Bartels days was plotted in Figure 3 for the periods 1985–1989, 1992–1996 and 1990–1991. The first two periods were chosen to correspond to the two different phases of the solar bipolar magnetic field and the third one to the solar polar field changeover period (Table I) (Webber and Lockwood, 1988; McKibben *et al.*, 1995). This figure shows that the distribution of the stream occurrence in Bartels days is very similar in both periods (premax and postmax). A tendency for a four-sector behaviour of streams located in the positive-polarity of the IMF is apparent, while a two-sector structure for the negative polarity is noted. During the maximum period the structured interplanetary magnetic field is more complicated and only a phase opposition between the positive and negative polarity tends to appear.

TABLE I

Solar magnetic field polarity during the last three solar cycles and some features of the cosmic-ray modulation (Webber and Lockwood, 1988; McKibben *et al.*, 1995; Mavromichalaki, Belehaki, and Rafios, 1998)

Polar field changeover	Solar field polarity	Drift effects (positive particles)
N − to + Feb. 1971		
S + to − Sep. 1969		
	Outward (positive)	Down from polar regions and outward along current sheet
N + to − May 1980		
S − to + Sep. 1980		
	Inward (negative)	Inward along current sheet
N − to + Jan. 1990		
S + to − June 1991		
	Outward (positive)	Down from polar regions and outward along current sheet

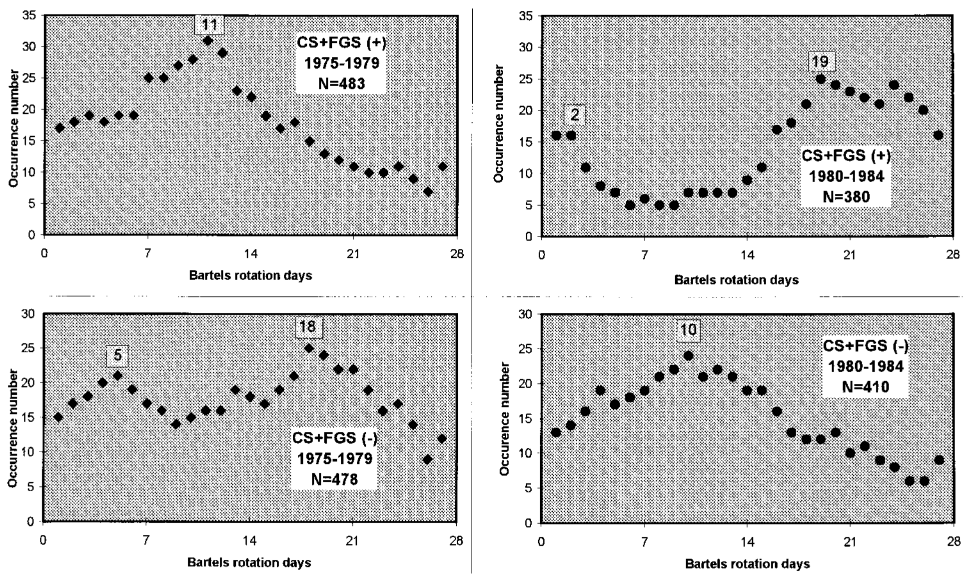

Figure 4. Number of days within a Bartels rotation during which a high-speed stream is observed at Earth for the two periods 1975–1979 (premax) and 1980–1984 (postmax).

It is interesting to compare these results with the corresponding ones for the period 1975–1984. The occurrence of the streams for the premax period (1975–1979) and the postmax period (1980–1984) are shown in Figure 4. It is noted that a phase opposition between the positive and the negative polarity appeared. A four-sector structure is noted in the negative polarity in the premax period and in the positive polarity in the postmax period, in contrast to the two-sector structure of the rest of cases. The preferred day in Bartels rotation is day 10 for the positive polarity in the time span 1975–1979, that is the preferred day for the negative polarity in 1980–1984. In opposition, the preferred days for the negative polarity in 1975–1979 and also for the positive polarity in the 1980-1984 are on average days 4 and 18. On the other hand, Lindblad (1981) studied the two epochs 1964–1970 and 1971–1975 corresponding to the two different phases of cycle 20 and showed that the distribution of Bartels days of the regular streams had the same behaviour in both epochs. He explained these observations in terms of a tilted dipole model of the solar interplanetary field, with different tilt for the two epochs 1964–1970 and 1971–1975. From this comparison it is obvious that this opposite behaviour of the streams with the Bartels days in the two different phases of the solar cycle is due to the polarity reversal of the solar magnetic field, as the polarity of the solar field reverses sign about every 11 years near the time of maximum solar activity. Thus successive activity minima are characterised by a different solar field polarity. The times of magnetic field polarity change (McKibben *et al.*, 1995) along with some of the features of the cosmic ray modulation that we have noted for the last three solar cycles are presented in Table I (Webber and Lockwood, 1988; Mavromichalaki, Belehaki and Rafios, 1998). These features can certainly be related to the 22-year magnetic field cycle (see also Storini, 1997, and references therein).

According to the above we can interpret this different behaviour of the sector structured IMF associated with the high-speed plasma streams during odd and even solar cycles as the result of the Hale-cycle effect which means the two parts of the basic 22-year solar periodicity.

In a further study the data sample was divided into smaller periods of two-years length. The stream distributions as a function of the Bartels days for the positive and negative IMF polarities are shown in Figure 5 (although results from this figure are not so clear, as those from previous figures). The positive polarity presents a tendency for a four-IMF-sector structure in contrast to the negative one which is more characterized by a two-IMF-sector behaviour. A more complicated feature appears during the maximum period 1990–1991 (Figure 3). Tritakis and Mavromichalaki (1992), examining the inferred IMF data for the cycles 19 and 20, have pointed out that a two-sector structure is prominent during the extremes of the solar cycles, but a four-sector structure predominates during the intermediate years especially in the descending branch of each 11-year cycle.

In conclusion, the interplanetary magnetic field, as was observed by near-Earth spacecraft, tends to consist of two or four IMF-polarity sectors within a 27-day solar rotation period. Although a four-sector structure of the interplanetary mag-

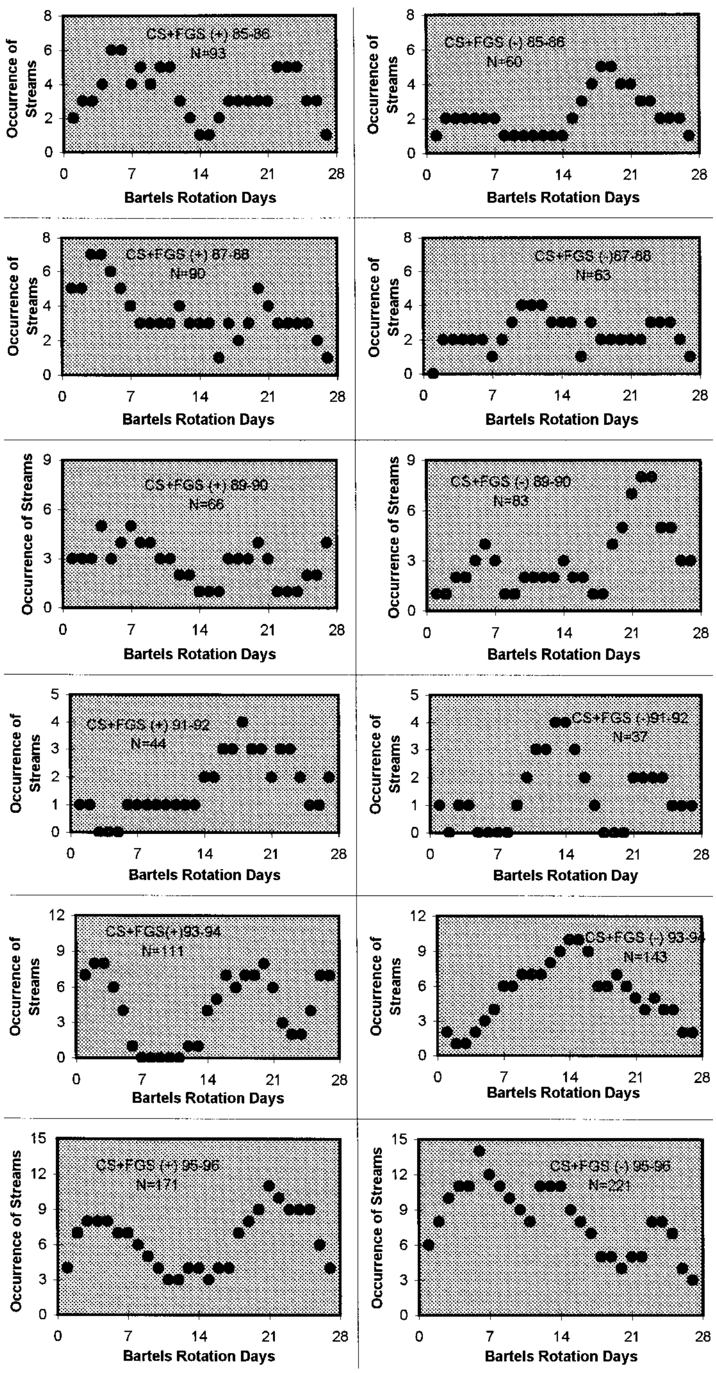

Figure 5. Stream occurrence distribution of Bartels days for periods of two-years length from 1985 to 1996.

netic field is mainly observed during the 22nd solar cycle, a two-sector structure is also observed in some cases within a 27-day rotation in which a corotating or flare-generated stream is observed near the Earth. This is related with the results of the 20th solar cycle where mainly a two-sector structure was apparent (Lindblad, 1981), although inspection of Svalgaard's list of inferred IMF polarities showed that a stable four-sector pattern of the interplanetary field was observed during several periods in 1964–1975 (Svalgaard, 1976). However, it is important to note that the inferred four-sector structure often consisted of two-sectors of long duration and two-sectors of rather short duration. So the disagreement is resolved, if it is assumed that IMF sectors of short duration, corresponding to minor warps of the neutral current sheet, do not give rise to high speed plasma streams (Lindblad, 1981). The observed differences in the distribution patterns between solar cycles 20, 21, and 22 may be attributed to the intrinsic differences in the solar activity and IMF among the solar cycles. For example 1964–1965 was a period of marked four-sector pattern of IMF, while 1974–1975 was dominated by two-sector solar wind streams (Lindblad, 1981; Rangarajan and Mavromichalaki, 1989).

4. Discussion

The magnetic field of the Sun exhibits two large-scale organized features: the polar fields and the solar sector structure. Both features have large spatial extent and can exist on time scales up to several years. In both cases the magnetic field intensity is weak and hence the structures are characterized by open field lines carried out by the solar wind between regions containing oppositely directed open field lines, which are separated by neutral sheets or current sheets. The intersections of these sheets with the ecliptic at 1 AU can be observed by spacecraft and are called 'sector boundaries' (Wilcox, 1968). Comparisons between the photospheric magnetic field and the interplanetary field near the ecliptic seem to suggest that the sector boundaries on the Sun are approximately in the north-south direction, crossing the equator and having a considerable extent in latitude perhaps up to 40° on both sides of the equator (Schatten, Wilcox, and Ness, 1969). Traditionally the polar fields have an approximately east–west oriented boundary or limit at times extending down to 55° latitude (Severny, 1971).

Based on theoretical considerations, Schultz (1973) interpreted the magnetic sectors due to multiple crossings of the solar equatorial plane by a large-scale, warped heliospheric current sheet. He suggested that the two-sector pattern sometimes observed arises from a tilted solar magnetic dipole component and the more commonly observed four-sector pattern from a quadrupole component. The tilted dipole model has been further discussed by Levy (1976), Alfvén (1977), and Villante *et al.* (1979) among others. Observations from Pioneer-11 showed the presence in interplanetary space of an equatorial current sheet tilted by about 15° to the solar equatorial plane during the period 1975–1977 (Smith, Tsurutani, and Rosenberg, 1978).

Strong support for these ideas has come from potential-field modelling of low-resolution measurements of the line-of-sight components of the photospheric magnetic fields (Schatten, Wilcox, and Ness, 1969; Wilcox, Hoeksema, and Scherrer, 1980). A spherical source surface is assumed to exist at some height, usually $\sim 2.5\ R_0$, below which the coronal magnetic field is potential (current-free) and above which the field lines are stretched radially through the action of the solar wind. The neutral line on this surface is taken to be the footpoints of the heliospheric current sheet and the agreement with interplanetary magnetic field measurements in the ecliptic plane is quite satisfactory (Hoeksema, Wilcox, and Scherrer, 1983). Furthermore, Hoeksema and Scherrer (1986) plotted the contributions of the dipole, quadrupole and octopole components of the source surface field strength throughout the solar cycle and found that the dipole component dominates but during much of the cycle the quadrupole component is comparable and even the octopole component is not negligible. Stewart (1987) describing synoptic plots of solar radio noise storms in the interval 1973 to 1984 concluded that the correlation found for noise storms and the photospheric polarity suggests strongly that the sector structure of the interplanetary magnetic field results mainly from the clustering in longitude of active region complexes (Gaizauskas *et al.*, 1983).

Girish and Prabhakaran (1988) investigated the effect of the presence of a magnetic quadrupole in addition to the magnetic dipole in the heliomagnetic field in shaping the HCS geometry and the resulting IMF variations near Earth. It was seen that the quadrupole moment introduces a north–south asymmetry in the HCS. This also causes interesting changes in the heliographic latitude location of it, where the reversal of the sign of the dominant polarity of the IMF takes place during a solar rotation period, depending on the active phases of the dipole and quadrupole components of the solar magnetic field. The effect of this type of HCS on the 'mean sector width' changes of the IMF near the Earth is in agreement with HCS observations during 1974–1977 compared to the shifted sinusoidal HCS model (Tritakis, 1984a, b).

Previous studies of interplanetary magnetic sector boundaries have been based on the assumption that the field polarities can be determined by comparing the field directions to the nominal Parker spiral angle. Nowadays a new technique using the flow directions of $E > 2$ keV electrons relative to the fields is presented to determine field polarities. This technique compares characteristics of sector boundary crossings with those of directional discontinuities without changes in field polarities (Kahler and Lin, 1995).

Lindblad (1981) noted that the observed variation in the dominant polarity of the interplanetary field associated with the high-speed streams recorded at 1 AU was difficult to explain unless one assumes that the source regions of the plasma are at high-solar latitudes and are asymmetric with respect to the solar rotation axis. He proposed a phenomenological model in which the occurrence peak of high-speed streams located in positive-polarity sectors during the premax period 1964–1970 was caused by plasma flow originated mainly in the southern region of the Sun, while during the postmax period 1971–1975 positive-polarity occurrence peak was due to plasma flow from the northern polar region. As it was necessary to hypothesise different tilted dipole configurations for the periods 1964–1970 and 1971–1975, Lindblad (1981) postulated a combination of a polar dipole field of the Sun and a low-latitude, sectored, photospheric magnetic field (Svalgaard, Wilcox, and Duvall, 1974). According to this the polar dipole field of the Sun reverses one or two years after solar maximum, while the polarity of the low-latitude, sectored, magnetic structure of the photosphere is constant over the solar cycle. The combined axial and low-latitude fields produced tilted dipole configurations during the analysed cycle (practically cycle No. 22) similar to those observed during solar cycle 20 (even cycles), it means a two- or four-sector structure of the interplanetary magnetic field in the two branches of the even cycles.

In this contribution a similar model of the interplay between the polar magnetic fields of the Sun and the solar sector structure during the solar cycle is outlined. As it is known in the beginning of the sunspot cycle, the polar fields are assumed to be quite regular and strong and of opposite polarity in the two hemispheres. Near the maximum of the cycle the polar fields are considerably weakened and shortly after maximum they reverse (Wilcox and Scherrer, 1972) and increase in strength and extent during the declining phase of the sunspot cycle. If we consider an even sunspot cycle, where the northern polar field is inward (−) during the early part of the cycle and a (outward/inward or +/−) sector boundary is at central meridian, the model predicts the following pattern; a streamer at high northern latitudes should be observed over the west limb together with corresponding southern streamer over the east limb. The current sheet, which separates regions of opposite polarity and marks the sector boundaries in the corona runs now NW–SE. At sunspot maximum the boundary is more in the N–S direction; later when the polar fields have completed their reversal the boundary runs NE–SW and the northern streamer should be observed over the east limb and the southern streamer over the west limb. An analogous pattern of course is expected for the other kind of sector boundary (inward/outward or −/+) (Svalgaard, Wilcox, and Duvall, 1974).

If we rotate these model patterns for seven days of solar rotation, this sector boundary and its associated current sheet will be at the limb, where we will see the sheet side-on. If the electron density is high enough the sheet may be visible as a fan-structure centred on the equator and extending to higher latitudes both northward and southward of the equator. The anticipated appearance of the current sheet and the magnetic polarity of the large-scale fields through one solar rotation is presented in Figure 6. It may very well be that the fan has a rather uniform brightness without too much internal structure, but this all depends on how the electron density varies along the sheet. The fan is expected to be more intense near the equator than at very high latitudes. To the right of each solar diagram in Figure 6 is shown the condition of the interplanetary magnetic field as it would be

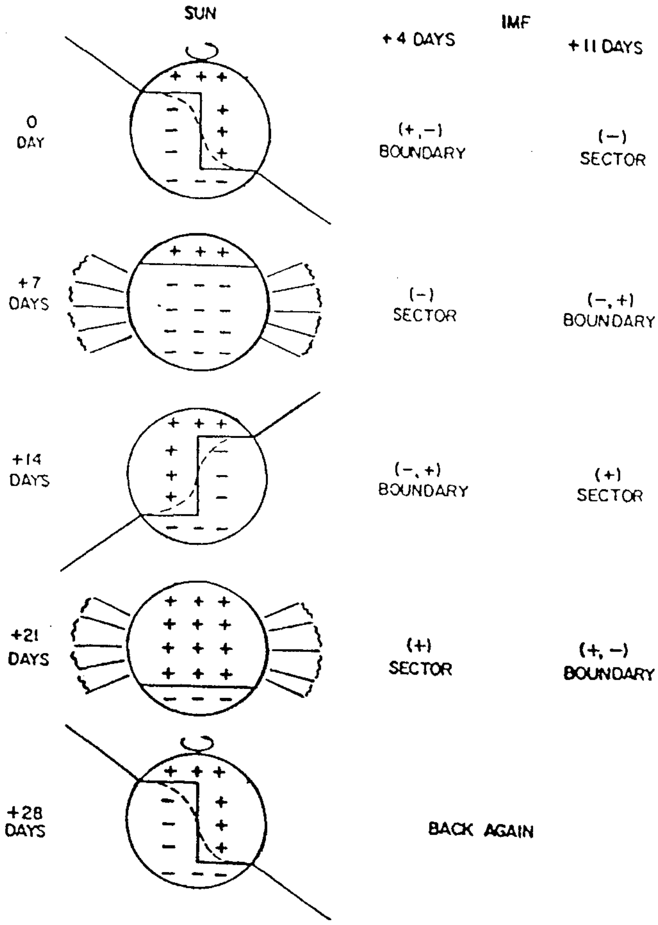

Figure 6. Changes in apparent location of coronal streamers and solar sector boundaries during one solar rotation assuming two sectors (after Svalgaard,Wilcox and Duvall, 1974). At the right is shown the condition of the interplanetary magnetic field (IMF) near the Earth following 4 days and 11 days respectively after the corresponding solar configuration at the left.

observed near the Earth at first 4 days and then 11 days after the corresponding solar structure shown to the left (Svalgaard, Wilcox, and Duvall, 1974).

So far we have been discussing the structural features for the case of only two magnetic sectors of opposite polarity per solar rotation. Extending the discussion and the predictions derived from it to a four-sector structure, the paired northern and southern streamers would then be about 90° apart in longitude instead of 180° as in the case with two sectors. Similarly, the systematic change of the coronal structure shown in Figure 6 would repeat twice during the solar rotation.

We believe that the above considerations can explain sufficiently our results about the behaviour of the occurrence rate of the fast streams in Bartels rotation days during the 22nd solar cycle. The differences between this cycle and the previous ones (21st and 20th cycles) may be attributed to the intrinsic differences in solar magnetic activity (Mavromichalaki *et al.*, 1997). The different behaviour of them in the premax and postmax period seems to be related to the polarity reversal of the polar magnetic field of the Sun. The possible effectiveness of the Hale cycle during even and odd solar activity cycles (Storini, 1995, 1997) on the occurrence of the fast solar wind streams is observable.

5. Conclusions

The following results can be drawn from all the above:

The interplanetary magnetic field, associated with the fast solar wind streams in Bartels rotation days, presents generally a four-sector structure during the years 1985–1996. This phenomenon is stronger in fast streams with positive IMF polarity, while for the streams with negative polarity there seems to appear a tendency for a two-sector structure. It is interesting to note that the two-sector structure of the IMF was also observed in the period 1964–1975 (Lindblad, 1981) whereas it is not a dominant IMF sector structure in the period 1975–1984.

Another important remark is the different feature of the occurrence rate of the streams with opposite IMF polarities in the ascending and in the declining branches of the solar cycle 21 (odd cycle) and the similar picture of them in the two epochs depicted in the cycles 20 and 22 (even cycles). This result gives evidence for a different behaviour of the high-speed streams in the sunspot cycles. The observed differences in the distribution patterns between solar cycles may be attributed to the intrinsic differences in the solar activity and IMF during the solar cycles as the distribution of the sources in the solar surface, the reversals of the polar magnetic field of the Sun, etc.

In addition, a tendency of the streams to occur at preferred Bartels days is confirmed. Well defined preferred days are generally the days 5 and 18 for the positive polarity and days 14 and 23 for the negative polarity in the 1985–1996 data set. The days 5 and 18 are also presented in the distribution patterns of the corotating streams located in positive-polarity sectors of the IMF, while days 14 and 23 are observed in the distribution pattern of the flare-generated streams located in negative polarity sectors. It is noteworthy that fast streams located in sector boundaries crossings seem also to occur in selected days of the solar rotation. The disagreement of the sector boundary cases distribution in the maximum of the examined time periods probably implies some kind of longitudinal relocation of the HCS induced by the differential rotation of the solar surface and the reorganization of the solar activity which has been determined to take place about the end of each 22-year cycle.

Finally the four- or two-sector structure of the IMF associated with high-speed streams is due to the relation between the sheet configuration and the position of the coronal holes thus controlling the polarity of their outgoing solar streams. Using the changes of the tilted magnetic dipole during an even sunspot cycle we have discussed a phenomenological model for the solar magnetic field structure proposed by Svalgaard, Wilcox, and Duvall (1974), postulating a combination of a polar dipole field and a low-latitude sectored photospheric magnetic field. According to this model the polar dipole field of the Sun reverses one or two years after solar maximum, while the polarity of the low latitude, sectored magnetic structure of the photosphere is constant over the solar cycle. The combined axial and low latitude fields will produce tilted dipole configurations similar to those observed during solar cycles 20 and 22. The features which are found in solar cycle 21 can be explained by the reversal of the polar magnetic field of the Sun from parallel to antiparallel states of the magnetic moment relative to the angular velocity axis of rotation of the Sun (Page, 1995). The reversal of the sign of the dominant polarity of the IMF takes place during a solar rotation period depending on the relative phases of the dipole and quadrupole components in the solar magnetic field which shapes the heliospheric current sheet geometry (Girish and Prabhakaran, 1988).

A further examination of the distribution of high-speed solar wind streams as a function of Bartels rotation days for short time intervals as well as during other solar cycles may give more evidence for the behaviour of the sector structured magnetic field and may make it possible to infer the nature of the warp in the heliospheric current sheet during different epochs.

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