FLUCTUATIONS OF THE SOLAR DYNAMO OBSERVED IN THE SOLAR WIND AND INTERPLANETARY MAGNETIC FIELD AT 1 AU AND IN THE OUTER HELIOSPHERE

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(Received 23 September 2003; accepted 15 March 2004)

Abstract. Recent helioseismic observations have found strong fluctuations at a period of about 1.3 years in the rotation speed around the tachocline in the deep solar convection layer. Similar mid-term quasi-periodicities (MTQP; periods between 1 – 2 years) are known to occur in various solar atmospheric and heliospheric parameters for centuries. Since the deep convection layer is the expected location of the solar magnetic dynamo, its fluctuations could modulate magnetic flux generation and cause related MTQP fluctuations at the solar surface and beyond. Accordingly, it is likely that the heliospheric MTQP periodicities reflect similar changes in solar dynamo activity. Here we study the occurrence of the MTQP periodicities in the near and distant heliosphere in the solar wind speed and interplanetary magnetic field observed by several satellites at 1 AU and by four interplanetary probes (*Pioneer* 10 and 11 and *Voyager* 1 and 2) in the outer heliosphere. The overall structure of MTQP fluctuations in the different locations of the heliosphere is very consistent, verifying the solar (not heliospheric) origin of these periodicities. We find that the mid-term periodicities were particularly strong during solar cycle 22 and were observed at two different periods of 1.3 and 1.7 years simultaneously. These periodicities were latitudinally organized so that the 1.3-year periodicity was found in solar wind speed at low latitudes and the 1.7-year periodicity in IMF intensity at mid-latitudes. While all heliospheric results on the 1.3-year periodicity are in a good agreement with helioseismic observations, the 1.7-year periodicity has so far not been detected in helioseismic observations. This may be due to temporal changes or due to the helioseismic method where hemispherically antisymmetric fluctuations would so far have remained hidden. In fact, there is evidence that MTQP fluctuations may occur antisymmetrically in the northern and southern solar hemisphere. Moreover, we note that the MTQP pattern was quite different during solar cycles 21 and 22, implying fundamental differences in solar dynamo action between the two halves of the magnetic cycle.

1. Introduction

Using helioseismic observations in space and on ground, Howe *et al.* (2000) found strong fluctuations of the solar rotation speed with a period of about 1.3 years around the tachocline in the deep convection layer. The fluctuations existed during the whole time interval studied from 1995 to 1999. A very clear and significant 1.3-year periodicity was found around the solar equator up to about 30° of solar latitude. (A less clear and less significant 1.0-year periodicity was seen at latitudes above 40°. Measurements extended up to 60°). Since the tachocline is the probable

Solar Physics **221:** 337–349, 2004.

source of solar magnetic flux, the rotation speed fluctuations around the tachocline are expected to modulate the generation of new magnetic flux, i.e., the strength of the solar dynamo.

Interestingly, fluctuations of 1–2-year period, also called mid-term quasi-periodicities (MTQP; Mursula, Zieger, and Vilppola, 2003) are a persistent phenomenon in the heliosphere, as evidenced, e.g., by the 1.4-year power peak in a time series covering more than 200 years of auroral activity (Silverman and Shapiro, 1983), and by the occurrence of MTQP power in a nearly 160-year long series of geomagnetic activity (Mursula, Zieger, and Vilppola, 2003). Although MTQP related periodicities have appeared in literature for a long time, they received increasing interest after Richardson *et al.* (1994) found a strong 1.3-year periodicity (to be called here the Richardson or 1.3 *R* periodicity) in solar wind speed during solar cycle (SC) 22. It was subsequently shown (Paularena, Szabo, and Richardson, 1995) that the 1.3 *R* periodicity existed concurrently in geomagnetic activity and solar wind (SW) speed, and that it had its 160-year maximum during solar cycle (SC) 22 (Mursula, Zieger, and Vilppola, 2003). Szabo, Lepping, and King (1995) found the 1.3 *R* periodicity also in the north-south component of the interplanetary magnetic field. Gazis (1996) argued that the 1.3-year SW speed enhancements are of solar origin rather than evolutionary fluctuations due, e.g., to interaction regions.

On the solar side, Ichimoto *et al.* (1985) reported 17-month (1.4-year) fluctuations in flare activity in solar cycle 21. McIntosh, Thompson, and Willock (1992) found a slightly longer, 600-day periodicity (to be called here the McIntosh or 1.7 *M* periodicity) in the coronal hole area in the southern solar hemisphere during SC 21. This periodicity was found to dominate the cosmic ray intensity in SC 21 Valdes-Galicia, Perez-Enriquez, and Otaola, 1996; Mursula and Zieger, 1999), as well as to occur in SW speed at 1 AU and in geomagnetic activity in SC 21 (Mursula and Zieger, 2000). Moreover, it has been shown that MTQP periodicities seem to appear in SW speed at 1 AU (and in geomagnetic activity) as separate activations with a greatly varying amplitude and a period systematically alternating between and a shorter (about 1.2–1.4 years) and a longer (about 1.5–1.7 years) period from one cycle to another during the last 70 years (Mursula and Zieger, 1999, 2000) and even in the mid-19th century (Mursula, Zieger, and Vilppola, 2003).

Here we analyze the occurrence of mid-term quasi-periodicities in the solar wind and the interplanetary magnetic field at 1 AU and in the outer heliosphere using the data from the multi-satellite OMNI set (King, 1977) and from four interplanetary probes (*Pioneer* 10 and 11 and *Voyager* 1 and 2). The heliographic locations of these four probes in the heliographic inertial coordinate system are given in Figure 1. This paper is organized as follows. In the next section we will describe the data and the method used in this work. Section 3 will present our results on mid-term quasi-periodicities observed in the different heliospheric locations. In Section 4 we discuss the results and compare them to related solar and heliospheric observations. Finally, Section 5 presents our conclusions.

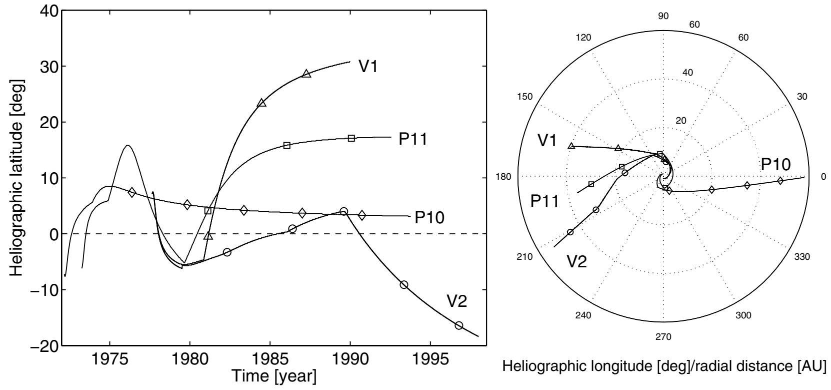

Figure 1. Spacecraft trajectories in the heliographic inertial coordinate system. Only the time intervals for which useful data exist have been depicted for each spacecraft. (a) Heliographic latitude as a function of time. Marks denote the spacecraft positions in 10 AU steps in radial distance. (b) Heliographic longitude and radial distance in polar presentation. (Earth has zero heliographic longitude on December 10). Marks denote times in 5 year steps. The innermost marks denote the position in 1975 for *Pioneers* and 1980 for *Voyagers*.

2. Data and Method

We use here the wavelet transformation technique to produce dynamic power spectra in order to find the possible quasi-periodicities in the different heliospheric variables. The hourly data from the combined OMNI data set and the various heliospheric probes were first averaged to 27-day running means. Thereafter, the remaining data gaps were filled using linear interpolation, and the data were resampled to daily sampling. Finally, the overall average was removed and the wavelet transformation was calculated using the complex Morlet wavelet (Lagoutte *et al.*, 1992). The complex Morlet wavelet consists of cosine and sine oscillations with a Gaussian window as its real and imaginary parts, respectively. Using the classical Morlet wavelet value of $\omega_0 = 5.34$ for the mother wavelet angular frequency (Lagoutte *et al.*, 1992) and $\sigma = 1$ (2, respectively) for the width of the Gaussian window (Holter, 1995), the frequency resolution corresponding to the half-width power (3 dB amplitude) decrease is $\pm\,15.6\%$ ($\pm\,7.8\%$) and the time resolution at period T is 1.42 T (2.83 T). The modulus square of the wavelet amplitude gives the power of the signal which is then depicted as a dynamic spectrum to be called here the wavelet dynamic spectrum (actually the wavelet scalogram).

3. MTQP at 1 AU and in the Outer Heliosphere

The wavelet dynamic spectrum (for $\sigma = 2$) of SW speed at 1 AU is shown in Figure 2. The strong 1.3 R periodicity dominates the SW speed fluctuations from 1988 to 1995. A weaker 1.7 M periodicity is seen from mid-1970s to mid-1980s.

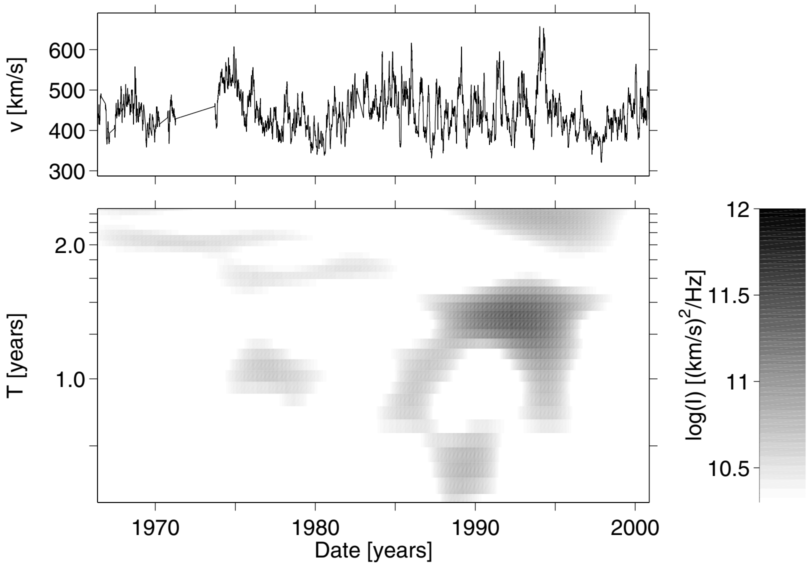

Figure 2. Time series and dynamic wavelet spectrum ($\sigma = 2$) of solar wind speed (v) at 1 AU in 1967–2000. The dynamic spectrum shows the fluctuations for periods $T = 0.68$–2.74 years (250–1000 days). Grey scale intensity (I) is given on the right.

(In detail, the period seems to be slightly shorter, about 1.6 years, before 1980 and longer, about 1.7 years thereafter). We note that the spectrum in the early 1970s is distorted because of fairly long data gaps in SW observations. A more correct view of the quasi-periodicities at this time is obtained from the dynamic spectrum of geomagnetic activity, according to which (see, e.g., Figure 2 in Mursula and Zieger, 2000) the dominant periodicity in early 1970s has a period of about 1.3 years, i.e., close to the Richardson periodicity. Thus, e.g., the roughly 2-year periodicity at this time in Figure 2 is an artifact due to the SW data gaps. However, since most observations in the outer heliosphere were made after mid-1970s we leave the earlier times with less concern in this paper and concentrate on solar cycles 21 and 22. (We also note that Figure 2 depicts intermittent power at the period of one year. This has been shown to be due to the fact that the SW speed distribution is systematically north-south asymmetric across the heliographic equator during solar minima (Zieger and Mursula, 1998; Mursula and Zieger, 2001; Mursula, Hiltula, and Zieger, 2002). Therefore we do not consider the related 1-year fluctuations within the class of MTQP fluctuations.

Figure 3 depicts the wavelet dynamic spectrum (for $\sigma = 1$) of the SW speed observed at *Voyager* 2. The 1.3 *R* periodicity appears in the *Voyager* 2 SW speed from 1988 to 1995. Richardson *et al.* (1994) showed the similarity of the 1.3-year fluctuations at 1 AU and *Voyager* 2 using the SW speed time series. Figures 2 and 3 depict the similarity of the two dynamic spectra for the 1.3 *R* periodicity and even for the 1.7 *M* periodicity for the overlapping time interval in early 1980s.

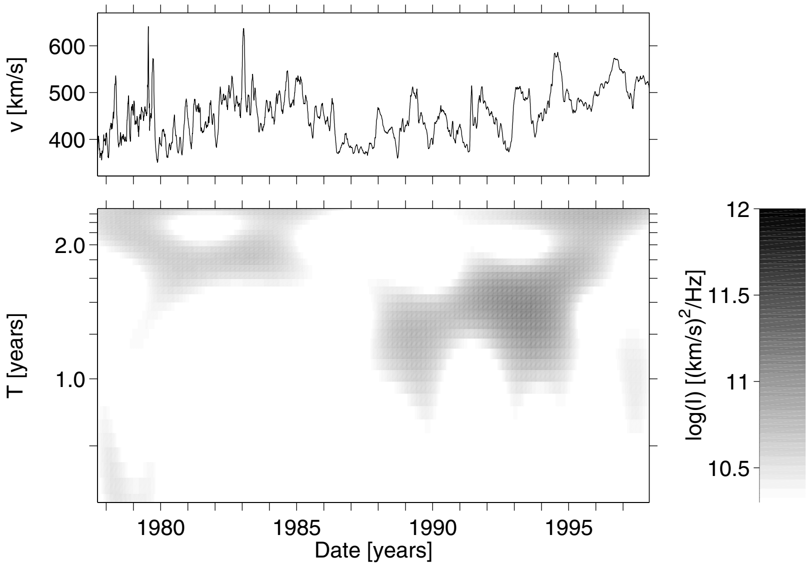

Figure 3. Time series and dynamic wavelet spectrum ($\sigma = 1$) of SW speed at *Voyager* 2 during 1978 –1997.

(*Voyager* 2 depicts a two-burst structure for 1.3 *R* with slightly different frequencies. A similar structure can also be seen at 1 AU when using the same, higher time resolution dynamic spectrum with $\sigma = 1$; not shown). Note that the exact periods at *Voyager* 2 are Doppler-shifted slightly longer than those observed at 1 AU because of the outward motion of *Voyager* 2 and the finite SW velocity. (Therefore, e.g., the exact period in Figure 3 in early 1980s is 1.8 years).

The spectral pattern for *Pioneer* 10 SW speed observations (see Figure 4) roughly follows the above observations. The 1.7 *M* periodicity is seen from 1980 to 1984, and the 1.3 *R* periodicity is weakly seen from 1988 until the end of *Pioneer* 10 SW data in 1995. (The enhancement around 1990 is mostly above 2 years). The SW speed measured at *Pioneer* 11 (not shown) depicts the 1.7 *M* periodicity from 1978 to early 1982 (with a similar small increase in period as simultaneously seen at 1 AU). There is also some evidence for the 1.3 *R* periodicity in *Pioneer* 11 from 1989 until 1992 (Gazis, Richardson, and Paularena, 1995) when *Pioneer* 11 SW data ends. However, the few 1.3 *R* oscillations seen in *Pioneer* 11 are weaker than the similar oscillations in *Voyager* 2 or at 1 AU. Also, as noted by Gazis, Richaredson, and Paularena (1995), the *Pioneer* 11 SW speed observations in earlier years are affected by solar cycle changes. (SW data from *Voyager* 1 existed only for 1978–1981, not enough to be useful for this study).

Figure 5 depicts the wavelet dynamic spectrum ($\sigma = 2$) of the IMF intensity at 1 AU. It is clear that the MTQP periodicity pattern in IMF intensity is quite different from that seen in SW speed at 1 AU (Figure 2). First of all, there is no indication of the 1.3 *R* periodicity in SC 22. The dominant structure in IMF

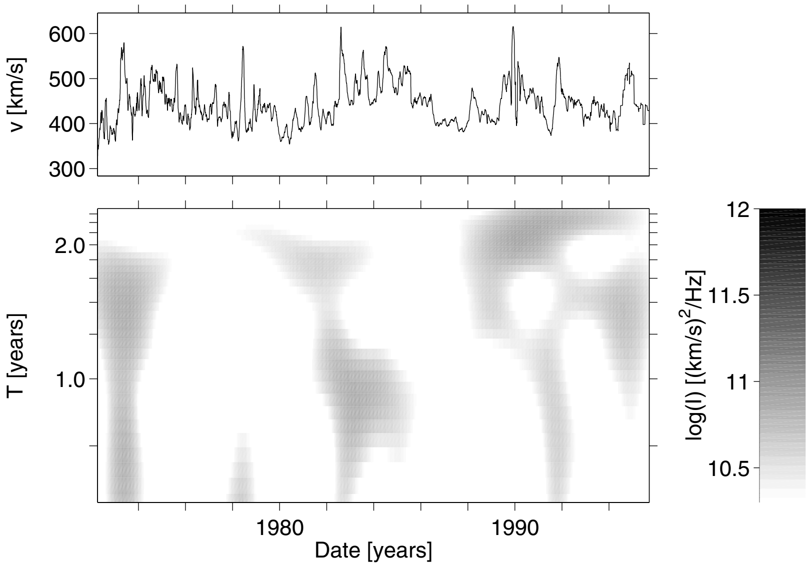

Figure 4. Time series and dynamic wavelet spectrum ($\sigma = 1$) of SW speed at *Pioneer* 10.

spectrum (Figure 5) is the 1.7 *M* periodicity which starts already in the mid-1970s and has its maximum around 1990. The period of these fluctuations agrees with the simultaneous variations observed in the mid-latitude coronal hole area (McIntosh, Thompson, and Willock, 1992). As mentioned above, the 1.7 *M* periodicity was also seen in SW speed around 1980 at 1 AU (Figure 2) and in the early 1980s at *Voyager* 2 (Figure 3), *Pioneer* 10 (Figure 4) and *Pioneer* 11. Note that the latter two detected the maximum of 1.7 *M* fluctuations in SW speed in 1981–1982, i.e., at the same time as the maximum of coronal hole fluctuations was observed (McIntosh, Thompson, and Willock, 1992). While the fluctuations of the coronal hole area (or boundary) can naturally explain the SW speed oscillations, the IMF intensity variations are related to fluctuations of the open solar magnetic field. (Note also that there is an indication of a 1.3 *R* periodicity in the IMF intensity during SC 20. Although the related power is fairly weak, the observation agrees with the simultaneous 1.3 *R* periodicity in SW speed and geomagnetic activity (Mursula and Zieger, 2000)).

Finally, Figure 6 shows the the wavelet dynamic spectrum (for $\sigma = 1$) of the IMF intensity at *Voyager* 1. (We have compensated the decrease with radial distance from the Sun by scaling the IMF with the radius.) The dominant MTQP structure in Figure 6 is the 1.7 *M* periodicity which occurs strongly from the beginning of the data until 1982. There is also evidence for a similar small increase of the 1.7 *M* period as seen in SW speed at 1 AU and *Pioneer* 11 and in IMF at 1 AU. (All other structures in Figure 6 are insignificantly small or unreliable because of boundary effects). We note that the 1.7 *M* periodicity is also seen in the *Voyager* 2

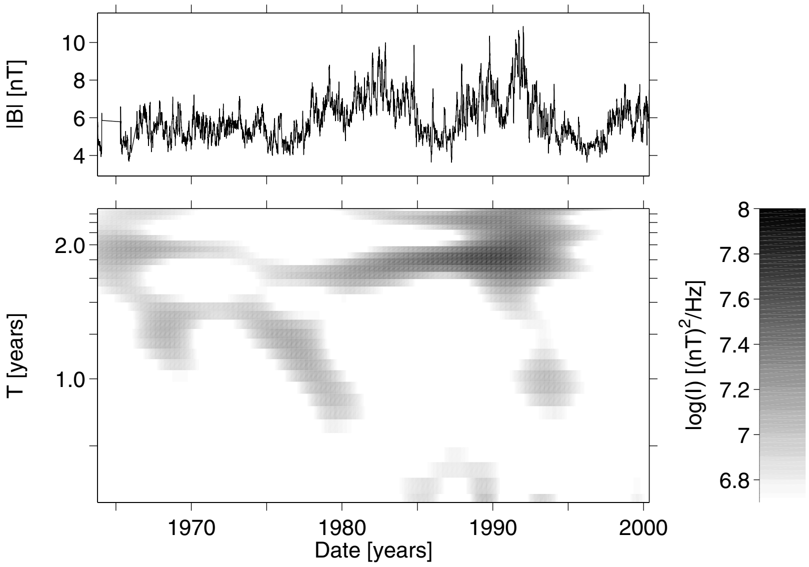

Figure 5. Time series and dynamic wavelet spectrum ($\sigma = 2$) of IMF intensity at 1 AU.

IMF intensity (not shown) but occurs there longer, until 1986. The same is true for the IMF intensity observed by *Pioneer* 11 where 1.7 *M* was seen from 1979–1986. (No useful IMF data exists from *Pioneer* 10.)

4. Discussion

The fluctuations in solar wind speed closely follow the changes in solar coronal holes. Moreover, since the solar wind propagates fairly radially, the fluctuations in coronal holes responsible for the SW speed fluctuations observed at 1 AU must have occurred fairly close to the solar equator. This is true also for the fluctuations leading to the 1.3 *R* periodicity in SW speed at 1 AU during SC 22 (and SC 20). These fluctuations have extended at least to 13° of southern latitude where *Voyager* 2 was in 1995 (see Figure 1 for *Voyager* 2 location), as demonstrated by the greatly similar 1.3 *R* pattern in SW speed at 1 AU and *Voyager* 2. The 1.3 *R* fluctuations start and end roughly at the same time at both sites, verifying, e.g., that the cessation of fluctuations at *Voyager* 2 is mainly temporal and not due to the changing latitude of the probe. (Note also that wave power in a dynamic spectrum for $\sigma = 2$, such as Figure 2, is slightly more spread temporally than for $\sigma = 1$, such as Figure 3.) Also, taking into account the Doppler shift and the time delay due to radial separation, the fluctuations are in phase at the two sites, indicating a coherent source in the Sun over this latitude range.

Note that *Pioneer* 10 detected the 1.3 *R* periodicity in SW speed at the same time as *Voyager* 2 and at 1 AU, and a weak signal of simultaneous 1.3 *R* fluctu-

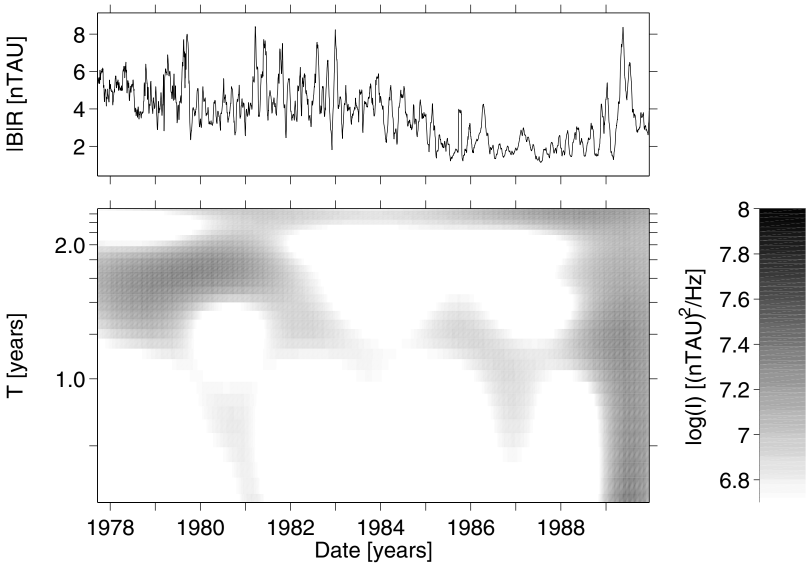

Figure 6. Time series and dynamic wavelet spectrum ($\sigma = 1$) of IMF intensity at *Voyager* 1 scaled by the radius.

ations was observed by *Pioneer* 11 at 18° of northern latitude. These heliospheric observations suggest that the 1.3 *R* fluctuations had a maximum amplitude close to the equator, decreasing outside the equatorial belt toward higher latitudes. These results are also in a good agreement with the helioseismic observations (Howe *et al.*, 2000), according to which the 1.3-year fluctuations have a maximum at the solar equator, being greatly reduced by 30° of solar latitude and vanish at 40° .

The heliospheric 1.7 *M* fluctuations, on the other hand, were not observed in helioseismic measurements. Because of the latitudinal expansion of IMF field lines toward the ecliptic (see, e.g., Wang and Sheeley, 1990), the 1.7 *M* fluctuations observed in the IMF intensity at 1 AU (see Figure 5) originate from outside the solar equator at mid-latitudes. Note also that the 1.7 *M* IMF fluctuations at 1 AU coexist with the 1.7 *M* periodicity in the coronal hole area (observed between 10° and 50° of southern latitude) during the simultaneous measurement time from mid-1970s to end of 1980s (McIntosh, Thompson, and Willock, 1992).

The 1.7 *M* periodicity was observed in the IMF measured by all the (three useful) heliospheric probes. However, the duration of the 1.7 *M* periodicity in all of them was shorter than observed in the IMF at 1 AU. In particular, *Voyager* 1 detected a strong 1.7 *M* period in the IMF only until 1982 (see Figure 6). This is most likely related to the fact that this probe was flying toward rapidly increasing heliographic latitudes at this time, remaining above 20° since 1983 (see Figure 1). This shows that the source of 1.7 *M* fluctuations was also limited in solar latitude and did not occur at very high latitudes. On the other hand, the lower latitude probes *Voyager* 2 and *Pioneer* 11 observed the 1.7 *M* period in the IMF as long as 1986.

These results verify that the 1.7 *M* periodicity occurred at solar mid-latitudes. However, the latitudinal extent of coherent 1.7 *M* fluctuations was considerable since both *Voyager* 2 and *Pioneer* 11 see a quite similar new intensification of 1.7 *M* at 1984–1986 when their heliolatitudinal difference is some 15°. (Both are then at the radial distance of about 15–20 AU.)

Weak 1.7-year fluctuations were also observed in SW speed at 1 AU around 1980. These are most likely caused by the simultaneous 1.7 *M* fluctuations in the coronal hole area (McIntosh, Thompson, and Willock, 1992). It is interesting to note that the 1.7 *M* periodicity was slightly stronger in SW speed at *Voyager* 2 than at 1 AU (see Figures 2 and 3). This is probably because in the early 1980s *Voyager* 2 was below the ecliptic, thereby in a more advantageous location for observing the stronger 1.7 *M* fluctuations in the coronal hole area of the southern solar hemisphere (McIntosh, Thompson, and Willock, 1992). The 1.7 *M* fluctuations in SW speed continued until 1985 both at 1 AU and at *Voyager* 2. Thus the 1.7 *M* fluctuations in SW speed stop earlier than the same fluctuations in IMF both in *Voyager* 2 and, especially, at 1 AU. This is probably due to the withdrawal of coronal holes from low to higher latitudes after the solar minimum.

It is evident from the above results that the 1.7 *M* periodicity was the dominant periodicity during SC 21. There were strong related fluctuations in the open solar magnetic flux over a wide range of mid-latitudes, as verified by IMF observations, as well as in the coronal holes, as earlier found by McIntosh, Thompson, and Willock (1992). Some of the 1.7 *M* fluctuations occurred at sufficiently low latitudes in order to affect the properties of the solar wind observed, e.g., at Earth. The largest 1.7 *M* fluctuations in SW speed were found in 1982–1984 (see Figures 2 and 3) when the largest fluctuations were observed in coronal hole area. We have also seen evidence that the 1.7 *M* fluctuations in SW speed were stronger in the southern hemisphere, in accordance with related coronal hole observations (McIntosh, Thompson, and Willock, 1992).

The 1.7 *M* fluctuations in IMF continued to persist beyond SC 21, reaching their maximum intensity at 1 AU during the maximum of the next solar cycle 22. In addition, there were strong 1.3 *R* fluctuations at low solar latitudes, most likely in low to mid-latitude coronal holes, as evidenced by related fluctuations in solar wind speed at 1 AU and at the different heliospheric probes. Accordingly, there were two strong, simultaneous fluctuations during SC 22, one with the 1.3 *R* period at low latitudes, the other with the 1.7 *M* period at mid-latitudes. Thus the two consecutive cycles were more similar in their MTQP activity at mid-latitudes but very different at low latitudes. The different behaviour in coronal holes at low latitudes between SC 21 and SC 22 is most dramatically reflected in the observations of solar wind speed at 1 AU and the (strongly correlated) geomagnetic activity which observe the alternation of the (weaker but still significant) 1.7 *M* periodicity in SC 21 and the strong 1.3 *R* periodicity in SC 22. This alternation between a shorter (about 1.2 –1.4 years) and a longer (about 1.5–1.7 years) period is known to have persisted since the 1930s (Mursula and Zieger, 1999, 2000) and even in the mid-19th century

(Mursula, Zieger, and Vilppola, 2003). Moreover, the MTQP fluctuations mainly appear during a highly active Sun, thus giving further evidence of their relation to the dynamo action (Mursula, Zieger, and Vilppola, 2003).

Note that the helioseismic measurements showing the 1.3 *R* fluctuations in the deep convection layer started in 1995, i.e., almost at the same time as both 1.3 *R* and 1.7 *M* periodicities decreased their intensity at 1 AU to a nearly vanishing level (see Figures 2 and 5). Accordingly, there are, at least so far, no clear, simultaneous observations of these periodicities both in the deep solar layers and in the heliosphere. Since the MTQP power in the heliosphere is related to the overall level of solar activity (Mursula, Zieger, and Vilppola, 2003), their low level presently is probably related to the overall, surprisingly weak activity during the ongoing cycle. In fact, it has been shown that significant temporal changes have occurred in heliospheric MTQP power, and that the MTQP power in geomagnetic activity reached its 160-year maximum during SC 22, emphasizing the exceptional nature of SC 22 (Mursula, Zieger, and Vilppola, 2003). Accordingly, one may argue that considerably larger fluctuations would have been observed if helioseismic measurements had been made during SC 22.

Although there are no clear simultaneous MTQP observations both in the deep solar layers and in the heliosphere, it is reasonable to argue that the equatorial heliospheric 1.3 *R* periodicity corresponds to the equatorial helioseismic 1.3-year periodicity. Since the heliospheric observations suggest that the mid-latitude 1.7 *M* fluctuations are even more persistent than 1.3 *R* fluctuations, a question arises why the 1.7 *M* periodicity was not observed in helioseismic observations. Of course, it is possible that the absolute or relative intensities of the fluctuations at different latitudes may change from one cycle to another and that the 1.3 *R* periodicity at low latitudes in SC 23 is stronger than the mid-latitude 1.7 *M* periodicity. (This would, however, be in contradiction to the ordering expected from long-term alternation; Mursula and Zieger, 2000; Mursula, Zieger, and Vilppola, 2003). Interestingly, in addition to this possible temporal intermittency, there is also another possible explanation. The method used in the helioseismic observations (Howe *et al.*, 2000) can only reveal north-south symmetric fluctuations. Thus, if the 1.7 *M* oscillations in the northern and southern hemisphere are antisymmetric (out of phase), they would remain unobserved. In fact, such an antisymmetry was observed for the 1.4 *M* fluctuations of solar flares during SC 21 (Ichimoto *et al.*, 1985). Since flares are good indicators of the emerging magnetic flux it is reasonable to assume that the source of magnetic flux at mid-latitudes can be hemispherically antisymmetric.

Several questions on mid-term quasi-periodicities remain even after the present study. As observed earlier, the relative and absolute strengths of 1.3 *R* and 1.7 *M* fluctuations change in time. In particular, the 1.3 *R* and 1.7 *M* seem to appear in SW speed interchangably every second solar cycle (Mursula and Zieger, 2000; Mursula, Zieger, and Vilppola, 2003). This seems to be systematic and implies a fundamental difference between the two halves of the solar magnetic cycle. What explains this strange behaviour of the solar dynamo? Also, does differential rotation explain why the MTQP period at mid-latitudes is longer than at low latitudes? Are the longer, mid-latitude fluctuations really north-south asymmetric, at least during odd solar cycles? How wide in latitude do either of the two periodicities extend? In order to answer these questions and in order to see if changes in these fluctuations occur during the solar magnetic cycle in the solar core, it is extremely important to continue the helioseismic observations. It is also important to develop the helioseismic methods in order to detect possible antisymmetric oscillations. Moreover, these results give new strong emphasis to continue the observation of all basic heliospheric parameters (SW, IMF) at all possible locations in the heliosphere whenever possible.

5. Conclusions

We have reanalysed the solar wind and the interplanetary magnetic field data measured at 1 AU and in the outer heliosphere by *Pioneer* 10 and 11 and *Voyager* 1 and 2 probes in order to study the existence of fluctuations in the period range of 1–2 years ('mid-term quasi-periodicities, MTQP') in different locations of the heliosphere during the solar cycles 21 and 22. We have shown that two different and strong MTQP fluctuations have existed simultaneously in the heliosphere during SC 22. These periodicities were organized latitudinally, having their solar origin at different latitudes. The 1.3-year periodicity, the Richardson periodicity (Richardson *et al.*, 1994, 1.3 *R*), is strongest close to solar equator (in low-latitude coronal holes) and decreases toward higher latitudes, while the solar origin of the 1.7–1.8-year periodicity, the McIntosh periodicity (McIntosh, Thompson, and Willock, 1992; 1.7 *M*), is at mid-latitudes.

The equatorial 1.3-year periodicity in the heliosphere corresponds very well to the period and latitudinal occurrence of fluctuations of the solar rotation rate found in the deep convection layer by helioseismic observations (Howe *et al.*, 2000). Accordingly, although the exact physical mechanisms are yet unknown, our observations support the idea that such fluctuations in the convection layer indeed modulate the generation of magnetic flux which is then reflected as corresponding fluctuations on the solar surface. The fluctuations of the open magnetic flux and the coronal holes on the solar surface are then fairly directly reflected in the fluctuations of the IMF intensity and solar wind speed.

We have also studied the 1.7 *M* fluctuations in the heliosphere whose origin is located at solar mid-latitudes and which have, at least so far, not been observed in helioseismic measurements. We have argued that this may be due to the method of helioseismic observations which are only sensitive to north-south symmetric fluctuations while north-south antisymmetric fluctuations would remain unobserved. Interestingly, observations of fluctuations of coronal holes at this period range at mid-latitudes indicate a strong north-south asymmetry (McIntosh, Thompson, and

Willock, 1992). Also, fluctuations in flare activity during SC 21 have been found to be clearly north-south antisymmetric Ichimoto *et al.* (1985).

The 1.7 M fluctuations were found during both solar cycles 21 and 22, while the 1.3 R occurred during SC 22 but not during SC 21. This and other differences in the heliospheric MTQP pattern between solar cycles 21 and 22 suggest that the absolute and relative intensities of the fluctuations at different latitudes may greatly vary from one solar cycle to another, indicating strong differences in the dynamo action between the two halves of the 22-year solar magnetic cycle. We note that the strongest and most versatile MTQP pattern in the heliosphere was found during SC 22, when the MTQP fluctuations at 1 AU depicted their 160-year maximum according to geomagnetic activity (Mursula, Zieger, and Vilppola, 2003). Thus, the present, spatially superior but temporally more limited observations give further emphasis to the earlier results on mid-term quasi-periodicities based on spatially more limited but temporally more extended observations using geomagnetic activity (Mursula, Zieger, and Vilppola, 2003).

Acknowledgements

We would like to acknowledge the Academy of Finland and the Väisälä Foundation for financial support, and the National Space Science Data Center and the PIs of *Pioneer* 10 and 11, A. Barnes and E. J. Smith, and *Voyager* 1 and 2, J. W. Belcher, J. D. Richardson, and N. F. Ness, for data.

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