Annual and solar rotation periodicities in IMF components: Evidence for phase/frequency modulation

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[1] We study the annual periodicity and the solar rotation periodicity of the in-ecliptic components of the interplanetary magnetic field (IMF). It is well known that the annual periodicity undergoes a phase reversal in 11 years, reflecting the 22-year Hale cycle of the solar magnetic field. We construct a model where the annual periodicity of the IMF components is phase/frequency modulated by the Hale cycle, and show that this model can reproduce the observed properties of the annual periodicity. We find that the solar rotation periodicity depicts an analogous nodal structure and a phase reversal with a period of about 3.2 years, implying a new periodicity in the properties of the IMF. We demonstrate that, using the observed spectral width, the phase/frequency modulation model can satisfactorily explain this structure. We also note that taking into account the observed phase reversal in the solar rotation periodicity implies that the most persistent synodic solar rotation period in the in-ecliptic IMF components is 27.6 days, i.e., somewhat longer than recently suggested. *INDEX TERMS:* 3210 Mathematical Geophysics: Modeling; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2162 Interplanetary Physics: Solar cycle variations (7536)

1. Introduction

[2] It is known since long that the solar wind (SW) and the interplanetary magnetic field (IMF) have a strong tendency to repeat at the solar rotation (SR) period of about 27 days. This was first observed in the recurrent pattern of geomagnetic activity [*Broun*, 1876; *Maunder*, 1905]. Subsequent studies have verified this periodicity in different geomagnetic indices [*Shapiro and Ward*, 1966; *Shapiro*, 1967; *Fraser-Smith*, 1972; *Takalo et al.*, 1995], and solar wind and IMF parameters [*Gosling and Bame*, 1972; *Gosling et al.*, 1976; *Sargent*, 1985; *Mursula and Zieger*, 1996]. Recently, *Neugebauer et al.* [2000] did an extensive analysis of the radial IMF component and suggested that the exact period of 27.03 days is the dominant period over several decennia.

[3] The annual periodicity in the IMF Bx and By components is also known for quite a long time [*Rosenberg and Coleman*, 1969]. It arises from the latitudinal variation of the dominant IMF sector around solar minima, and the inclination of the solar rotation axis with respect to the ecliptic. Accordingly, during a positive polarity minimum there is a dominance of the away sector in the Fall while the toward sector dominates in the Spring. The situation is reversed one solar cycle later during a negative polarity minimum. Therefore, the phase of the annual periodicity of the IMF Bx and By components changes every 11 years and makes one full cycle during one 22-year magnetic polarity (Hale) cycle [*Hale et al.*, 1919]. In this paper we demonstrate the appearance of the polarity change in the annual periodicity and in the solar rotation periodicity of the in-ecliptic IMF components, and model this behaviour in terms of the phase/frequency modulation by the 22-year magnetic polarity cycle.

2. Annual Periodicity in IMF Components and its Phase Change

[4] Figure 1 depicts the power spectrum of the IMF Bx GSE-component for 1964–1995. (The power spectrum of By is very similar). We use the OMNI data set [see *King*, 1977] retrieved from the NSSDC web server. The power spectrum was calculated using 50-day IMF Bx running daily means in order to decrease data gaps and to remove short-period variations in data, in particular those related to solar rotation. Figure 1 shows that the power of annual periodicity is split to two broad peaks on either side of the one-year nominal value. (We note that the two other near-by peaks at about 0.8/year and 0.6/year are independent quasi-periodicities unrelated to the annual variation. [See, e.g., *Szabo et al.*, 1995; *Mursula and Zieger*, 2000]). As we will discuss later in more detail, the spectral splitting and the subsidiary peaks are known for long in several heliospheric parameters. Spectral splitting can arise if the annual periodicity is not stable but, e.g., changes in intensity over the 11-year solar cycle. Since the latitudinal distribution of IMF sectors indeed varies over the solar cycle, the amplitude modulation of annual periodicity is feasible and is commonly considered to be responsible for the observed splitting. However, in this paper we suggest another mechanism for spectral splitting in terms of the phase/frequency modulation of the annual periodicity by the 22-year solar magnetic (Hale) cycle.

[5] Figure 2a depicts the autocovariance function (ACF) of IMF Bx component for lags up to 30 years. (The ACF of IMF By is very similar). There is a strong tendency for the annual periodicity to repeat with the same phase (but decreasing amplitude) for about 3–4 years. At a lag of 4–6 years, the ACF experiences a node (amplitude roughly zero) and a phase change after which the annual variation is repeated with an opposite phase. There is a strong antinode (amplitude maximum) in the ACF with opposite phase at a lag of about 10 years. The opposite phase corresponds to the situation one solar cycle later when the away (toward) sector dominance has changed from Fall to Spring (Spring to Fall, resp.) after the turning of the solar magnetic field. The interval with an opposite phase ends at the second node of the ACF at a lag of 15–16 years after which the phase is changed back to the original. Accordingly, the next antinode at about 20-year lag has the same phase as before the first node. This second antinode corresponds to the situation one full solar magnetic cycle later. (Note that recent solar cycles are shorter, about 10 years, than the long-term average of about 11 years. Therefore the first antinode is at about 10 years and the second at 20 years. However, we wish to call the cycles 11 and 22 years long since this is the common practice). We note that this systematic change of the phase of the annual periodicity in the IMF Bx component over the Hale cycle can not be understood in terms of amplitude modulation which retains the annual phase the same. Instead, it gives strong evidence in favour of phase/

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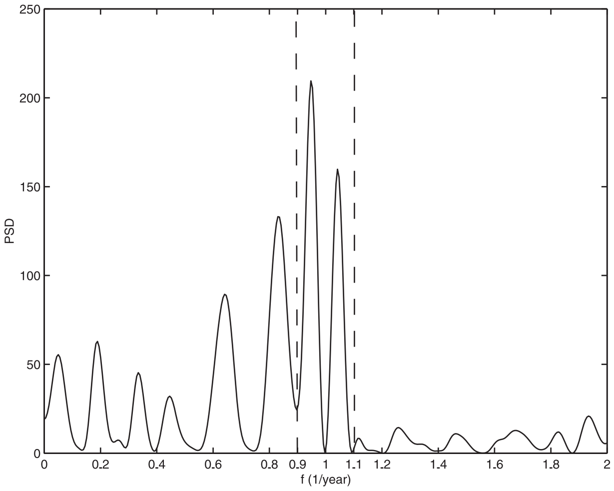

Figure 1. Power spectrum of IMF Bx component around the frequency of 1/year. Dashed lines denote the power included in annual periodicity.

frequency modulation. However, it is probable that amplitude modulation is also effective at some level, as indicated above.

3. Solar Rotation Periodicity in IMF Components and its Phase Change

[6] Figure 3 depicts the power spectrum of IMF Bx in 1964–1995 around the average solar rotation period of about 27.6 days. (We used daily IMF values interpolated by a constant value over data gaps. Note that the way of interpolation, or the repetitive data gaps due to the IMP 8 orbit have little effect on present results). The 27.6-day rotation period is very close to the synodic rotation period at the surface of the Sun's equatorial region [see, e.g., *Howe et al.*, 2000, and references therein]. According to Figure 3 it is evident that the power is divided to a rather large range of periods around this average, implying that the solar regions producing the

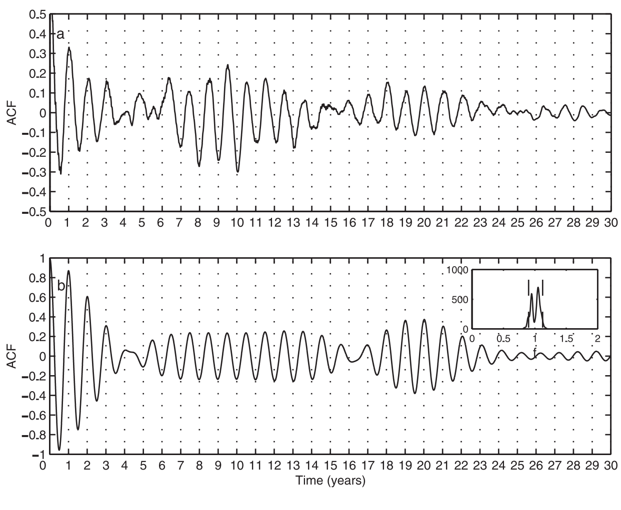

Figure 2. (a) ACF of IMF Bx component for lags up to 30 years. (b) ACF of the phase/frequency model of annual periodicity in IMF Bx. Inset shows the model power spectrum around the frequency of 1/year.

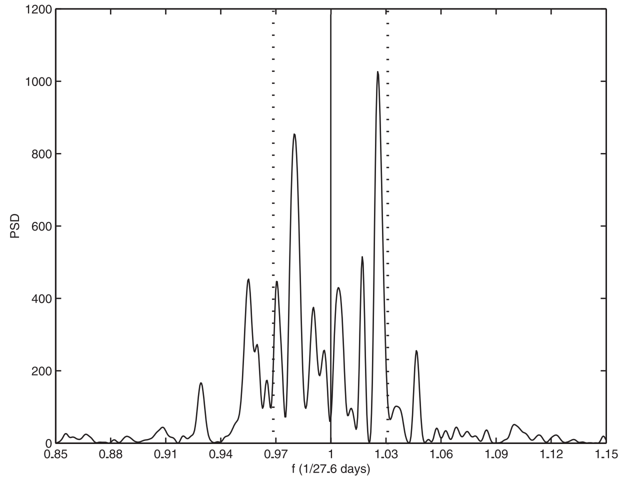

Figure 3. Power spectrum of IMF Bx component around the frequency of 1/(27.6 days). Dotted lines denote the power included in the solar rotation periodicity.

interplanetary magnetic field at 1AU are not always rotating at the same angular velocity. Figure 3 has some similarity with the power spectrum around one year depicted in Figure 1. In particular, there are two dominant peaks around the 27.6-day average at about 26.9 days and 28.2 days.

[7] In order to study the phase pattern of solar rotation periodicity we have depicted the ACF of IMF Bx component over 50 solar rotations in Figures 4a and 4b. These figures are the same except that in Figure 4a we have used the 27.6-day solar rotation period and in Figure 4b the 27.03-day period proposed by *Neugebauer et al.* [2000]. Accordingly, a slightly longer time interval is depicted in Figure 4a than in 4b. In each figure we have also marked with dotted lines the multiples of the respective solar rotation periods.

[8] Figures 4a and 4b show that there is a strong tendency for IMF Bx to repeat with a decreasing amplitude for about 9 solar rotations. At a lag of 10–11 rotations, the ACF experiences a node after which the rotation periodicity recovers, reaching an antinode at a lag of about 20–22 solar rotations. After this antinode the ACF develops a temporary two-peak structure and its amplitude is reduced. A minimum in ACF (an unclear node) is found at a lag of about 35 rotations and thereafter, the next antinode at a lag of about 42–43 rotations, i.e., after some 3.2 years. We note that this implies a new type of periodicity in the in-ecliptic IMF components.

[9] Let us now compare how well the two rotation periods used in Figures 4a and 4b can reproduce the node and phase structure of the ACF. The 27.6-day period fits better to the first 10 ACF maxima than the 27.03-day period which tends to be too short and whose multiples therefore occur increasingly too early for these maxima. After the first node, the multiples of the 27.6-day period fit the ACF minima rather than maxima, indicating that the phase of the solar rotation periodicity is reversed. The anti-phasing interval lasts until and slightly beyond the first antinode at about 20–22 solar rotations until a normal phase is recovered at the second antinode some 20 rotations later. (Note that the phase recovery is also seen in the development of the two-peak structure where the 27.6-day multiples change from the minima to the increasing first peak of the evolving two-peak structure). On the other hand, the 27.03-day period retains the same phase throughout the depicted time interval, and its multiples always roughly follow the ACF maxima. Note also that the best fit occurs around the ACF antinodes while in the intervening intervals, the multiples of the 27.03-day period seem to be either

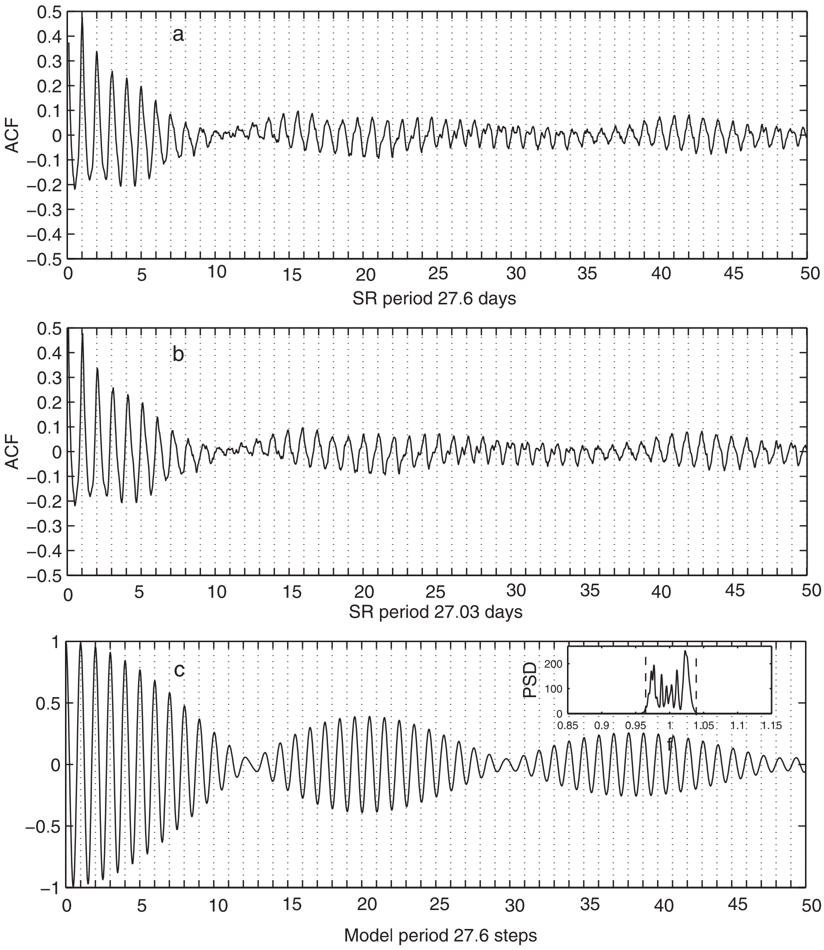

Figure 4. (a) ACF of IMF Bx component for lags up to 50 solar rotations. Multiples of the 27.6-day period are marked with vertical dotted lines. (b) Same as in a, but multiples are for the 27.03-day period. (c) The ACF of the phase/frequency model of solar rotation periodicity in IMF Bx. Inset shows the model power spectrum around the frequency of 1/(27.6 days).

too late or too early, in analogy to the situation during the first 10 solar rotations.

4. Phase/Frequency Modulation Model

[10] In order to simulate the phase/frequency modulation we have constructed a simple periodic signal (period a) with a variable phase

$$s(t) = \cos[2\pi t/a + k \cdot \sin(2\pi t/b)], \quad (1)$$

where k is a modulation index which controls modulation efficiency. The modulation index is related to the frequency deviation df caused by modulation through $k = df/fm$, where fm is the modulating frequency ($b = 1/fm$). (The sinusoidal form of Equation (1) corresponds, strictly speaking, to frequency modulation. Phase modulation could be generated, e.g., by a square function. However, both phase modulation and frequency modulation models lead to essentially similar results).

[11] In the case of annual periodicity we have a = 365 days. Modulation period is now taken to be the Hale cycle with $b = 20 * 365$ days. Furthermore, we obtain an estimate for the deviation df of annual periodicity from the power spectrum of IMF Bx depicted in Figure 1. Including the power around the two main peaks (the region between the two dashed vertical lines in Figure 1) yields df = 0.1/year = 0.00027/day from which we get the modulation index k = 2.0 for annual periodicity in IMF.

[12] We have calculated the ACF of this phase/frequency modulated model signal for annual periodicity in IMF and depicted it in Figure 2b. Taking into account the simplicity of the model, the similarity of this model ACF and the experimental ACF (Figure 2a) is outstanding. The model reproduces accurately the phase structure of the signal with phase turning every 10 years. It also locates the nodes and antinodes of the ACF quite reliably. The overall absolute level of the model ACF, which completely ignores random effects, is naturally slightly too high. Still, curiously, the maximum amplitudes of the two ACFs at the first antinode are quite similar. Finally, we note that the power spectrum of the model signal, depicted in the insert of Figure 2b, has a similar two-peak structure as the experimental power spectrum. Accordingly, phase/frequency modulation can correctly reproduce the observed spectral splitting.

[13] For solar rotation periodicity we use a = 27.6 days while the modulation period is the same as above. From the power spectrum of IMF Bx (Figure 3) we obtain an estimate for the related deviation df. Including the two main peaks within a symmetric region around the 27.6-day average (the region between the two dotted vertical lines in Figure 3) yields df = 0.0011/day. From this we get the modulation index k = 8 for solar rotation periodicity in IMF. The ACF of the phase/frequency modulated model signal for solar rotation periodicity in IMF is depicted in Figure 4c. Again, taking into account its simplicity, the model performs surprisingly well. It reproduces accurately the phase

structure of the signal and the turning of the phase from antinode to antinode. It also locates the first node very well. However, the first antinode is slightly too early and the model cycle is slightly too short, about 40 solar rotations instead of 41–43.

[14] Note that the absolute level of the experimental ACF is clearly lower for solar rotation periodicity than for annual periodicity. This suggests that rotation periodicity is less strong and more vulnerable, e.g., to random effects which tend to decrease this periodicity. This also implies that it is more difficult to model the rotation periodicity with the same simple model as successfully as the annual periodicity, and explains the larger difference in the absolute levels of the experimental and model ACFs. Finally, we note that the power spectrum of the model signal, depicted as a small insert in Figure 4c, has a quite similar two-peak structure as the experimental power spectrum (see Figure 3).

5. Discussion and Conclusions

[15] *Coleman and Smith* [1966] suggested that the subsidiary peaks in the power spectra of geomagnetic activity near 27 days are due to the amplitude modulation of rotation periodicity by the annual cycle. However, *Shapiro* [1967] pointed out that annual variation is not strong enough for amplitude modulation to be effective. *Fraser-Smith* [1972, 1973] showed that the power at 27 days consists only of a doublet with no central peak and explained this by the amplitude modulation according to the solar cycle. Here we have shown that the phase/frequency modulation according to the 22-year solar magnetic cycle may also produce a similar spectral splitting, and can explain the observed two-peak structure in the annual periodicity of the in-ecliptic IMF components.

[16] We emphasize that the systematic change of the phase of the annual periodicity in the IMF components over the Hale cycle (see Figure 2a) can not be understood in terms of amplitude modulation alone. We have shown that a simple phase/frequency modulation model in which the phase of annual periodicity is modulated by the Hale cycle can outstandingly well reproduce all the main characteristics of the annual variation of the horizontal IMF components. In particular, it reproduces the node-antinode structure of the autocovariance function, as well as the turning of the phase from one solar cycle to another. This gives compelling evidence in favour of phase modulation of the annual variation of IMF components. However, in addition, some amplitude modulation may exist at some level.

[17] *Neugebauer et al.* [2000] recently reanalysed solar rotation periodicity in radial IMF component and suggested that, although rotation period may significantly vary with time, the most persistent period over very long time intervals of several decennia is 27.03 days. This period is marked with vertical lines in Figure 3b of the IMF Bx ACF. The suggestion by *Neugebauer et al.* [2000] corresponds to our observation that multiples of the 27.03-day period fit to the maxima, not the minima, of the ACF over the whole time interval, thus keeping the same phase. Although not always fitting sharply at the ACF maxima (see earlier discussion), the 27.03-day period is still the period which fits these maxima in the best possible way. This observation is a restatement of the suggestion by *Neugebauer et al.* [2000]. Accordingly, it would seem that the 27.03-day period is the most persistent rotation period over very long time intervals.

[18] However, there are strong objections against this interpretation. In particular, the node-antinode structure of the ACF (see Figure 4a) can not be understood in terms of the suggestion by Neugebauer et al. according to which one would expect a continuously decreasing ACF amplitude. We emphasise that according to the suggestion by *Neugebauer et al.* [2000] there is no explanation for the recovery of the rotation periodicity after the first node. Instead, the slightly longer period of 27.6 days together with phase/frequency modulation can reproduce the existence of nodes and antinodes in the ACF of the in-ecliptic IMF components. We also found that multiples of the 27.03-day period are systematically either too early (as during the first 10 rotations) or too late while the multiples of the 27.6-day period fit overall better when one takes into account all extrema (both maxima and minima) of the ACF. Accordingly, we find compelling evidence that the most persistent solar rotation period in the in-ecliptic IMF components is 27.6 days. Moreover, we have found here that the solar rotation periodicity undergoes a phase reversal cycle which is approximately 3.2 years. This implies a new interesting periodicity pattern in the interplanetary magnetic field. We suggest that this pattern is related to fluctuations of the heliospheric current sheet which are repeated, on an average, every 3.2 years.

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