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The "Floor" in the Interplanetary Magnetic Field: Estimation on the Basis of Relative Duration of ICME Observations in Solar Wind During 1976 – 2000

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Abstract Measurement of the floor in the interplanetary magnetic field and estimation of the time-invariant open magnetic flux of the Sun require knowledge of closed magnetic flux carried away by coronal mass ejections (CMEs). In contrast with previous papers, we do not use global solar parameters to estimate such values: instead we identify different large-scale types of solar wind for the 1976 – 2000 interval to obtain the fraction of interplanetary CMEs (ICMEs). By calculating the magnitude of the interplanetary magnetic field B averaged over two Carrington rotations, the floor of the magnetic field can be estimated from the B value at a solar cycle minimum when the number of ICMEs is minimal. We find a value of 4.65 ± 0.6 nT, in good agreement with previous results.

Keywords Solar magnetic flux · Interplanetary magnetic field · Interplanetary coronal mass ejection

1. Introduction

One of the basic problems of physics of the Sun and the heliosphere is the estimation of the magnetic flux of the Sun which is carried away by the solar wind (e.g. Wang and Sheeley, 1995, 2003; Fisk and Schwadron, 2001; Riley, 2007; Lepri *et al.*, 2008 and references therein). Several models (see, for instant, the papers by McComas, Gosling, and Phillips (1992), Webb and Howard (1994), Owens and Crooker (2006, 2007), Owens *et al.* (2008a) and references therein) suggest that there is a minimum magnetic field, a floor of the open magnetic flux, which is constant (*i.e.* time-independent). Its value may be estimated using measurements during a solar minimum, as during a solar maximum coronal mass ejections (CMEs) carry away additional closed solar magnetic flux to the heliosphere.

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An estimation of the floor of the magnetic field has thus far been obtained by two methods.

(1) The magnitude B of interplanetary magnetic field (IMF) is compared with the phase of the solar cycle (sunspot number) and this dependence is extrapolated to zero sunspot number. This method produced an estimate of the floor of ~ 4.6 nT during the last 130 years (Svalgaard and Cliver, 2007).

(2) The magnitude B of IMF is compared with the daily CME rate observed with the LASCO coronagraph on the SOHO spacecraft (Owens and Crooker, 2006) and this dependence is extrapolated to zero CME rate. A floor value of 4.0 ± 0.3 nT has been obtained by similar methods (Owens *et al.*, 2008a).

Both methods use global characteristics of the Sun to estimate the floor, while IMF measurements near the Earth reflect only conditions near the ecliptic plane and hence magnetic flux generated by regions with different locations (latitudes) on the Sun: open magnetic flux from polar coronal holes at a solar minimum (see, *e.g.*, Luhmann *et al.*, 2009), closed magnetic flux from CMEs at low-latitude regions located near the Sun – Earth line at a solar maximum (see, *e.g.*, Valach, Hejda, and Bochnicek, 2007) and large-scale quasi-stationary latitudinal anisotropy may not be present in the heliosphere, owing to magnetic pressure balance (see, *e.g.*, Smith and Balogh, 2003; Lockwood *et al.*, 2004; Owens *et al.*, 2008b). Thus, anisotropy in various solar features at various phases of the solar cycle has various sorts of impacts on the IMF value, and the correspondence between IMF measurements and their solar sources (and solar characteristics) cannot be determined. The IMF values and ICMEs measured near the Earth are generated by the same solar regions and carry the characteristics of these regions.

Richardson, Cane, and Cliver (2002) did not use global solar parameters for a statistical study of the correlation between IMF and solar wind parameters and the *aa*-index of the magnetosphere: for a long time interval (1972 – 2000) they classified four types of solar wind ("CME-associated", "corotating high-speed", "slow", "uncertain" and total) and calculated three-rotation averages of IMF. They found that the minimum value, IMF ~ 5 nT, is observed for the total solar wind near the minimum of the solar cycle but they were not specifically interested in the floor and did not study the contribution of the "CME-associated" solar wind to the IMF.

In this paper we use the fraction of interplanetary CMEs (ICMEs) in the observation of the solar wind measured near the Earth (using the OMNI database) in 1976 – 2000 as a measure of the CME contribution to the heliospheric magnetic flux.

2. Method of Data Processing

Using the OMNI database of interplanetary measurements near the Earth (see the site http://omniweb.gsfc.nasa.gov and the paper King and Papitashvili (2005)), we classified several solar wind (SW) types during 1976 – 2000 into quasi-steady types: (1) heliospheric current sheet (HCS), (2) slow and (3) fast SW streams; and disturbed types: (4) corotating interaction regions (CIR), (5) sheath and (6) magnetic cloud (MC) and (7) ejecta as well as (8) direct and (9) reverse interplanetary shocks (see papers by Yermolaev *et al.*, 2009, 2010 and ftp://ftp.iki.rssi.ru/pub/omni/ for more details). Our analysis showed that MC was observed during $\sim 2\%$ of the total time of the observations, ejecta $\sim 20\%$, sheath before MC and ejecta $\sim 9\%$, CIR $\sim 10\%$, HCS $\sim 6\%$, fast SW streams $\sim 21\%$ and slow ones $\sim 31\%$. Identification of MC and ejecta events was carried out according to the standard criteria: low temperature, low ratio of thermal to magnetic pressure ($\beta < 1$) and smooth and rotating magnetic field (Burlaga *et al.*, 1981). MCs are a subclass of ICME and in contrast to ejecta, MCs have a higher and a more regular magnetic field (distinctions between them can be connected both with value of CMEs on the Sun and with the trajectory of the spacecraft relative to the axis of the magnetic flux rope in ICME) (Burlaga, 1991; Richardson and Cane, 1995; Russell and Mulligan, 2002; Cane and Richardson, 2003). On the average the solar wind at 1 AU for the years 1976 – 2000 can be classified as ICME material (*i.e.*, both MCs and ejecta) $\sim 22\%$ of the time.

Figure 1 shows temporal distribution of sheath + MC (left panel) and sheath + ejecta (right panel) observations as a stack plot of Carrington rotations (CR nos. 1636 – 1971) (Yermolaev *et al.*, 2010) and allows the reader to check our identification of the ICME (Yermolaev *et al.*, 2009). It is important to note that the data gap of the OMNI database (white regions in Figure 1) account for approximately 48% of the total time interval 1976 – 2000. Nevertheless, the figure shows that the rate of occurrence of ICMEs is high near a solar maximum and low near a minimum. Several CRs were covered by less than 100 hours of observation ($< 15\%$ of CR duration). These CRs have consequently been excluded from our analysis. We calculated the average magnitude B of the IMF and ICME fraction (F, the ratio of ICME duration to the total duration of interplanetary field and plasma data). The data were averaged over two CRs to increase the statistics. The parameters B and F are analyzed in the next section of this paper.

3. Results

The upper panel of Figure 2 shows a scatter plot of a 2-CR average of the IMF magnitude B as a function of the ICME fraction F. Different time intervals are highlighted: solar cycle minima are shown as open circles (1976 – 1977), open squares (1984 – 1987) and open triangles (1994 – 1998), whereas solar cycle maxima are shown as closed circles (1978 – 1983), closed squares (1988 – 1993) and closed triangles (1999 – 2000). There is a significant difference between solar minima and maxima of the solar cycle but no noticeable difference between cycles 21 and 22 for the same phases. The bottom panel shows average values and standard deviations of B calculated for various F bins: 0.0 – 0.05; 0.05 – 0.1 *etc*. Data in the 0.0 – 0.15 interval have been approximated by linear functions ($B = 5.92 + 8.08 \times F$ for maxima of the solar cycle and $B = 4.65 + 6.89 \times F$ for minima, respectively), and in the 0.2 – 0.45 interval by constant values ($B = 6.81$ and $B = 5.50$ nT, for solar maxima and minima, respectively). Our calculations show that the linear approximations obtained in the range of 0 – 0.15 are statistically significant at level 0.05. For a solar minimum $B = 4.65 \pm 0.6$ nT when $F = 0$. This value is our estimation of the floor in the interplanetary magnetic field during 1976 – 2000.

4. Discussion and Conclusions

Using the dependence of the magnitude of the interplanetary magnetic field B, averaged over two Carrington rotations, on the ICME fraction in measurements of the solar wind F during 1976 – 2000, we made an estimation of the floor in IMF (*i.e.* no ICME fraction) at a minimum of the solar activity of $B = 4.65 \pm 0.6$ nT. We could not find a significant difference between the floors during minima of different solar cycles because of the poor statistics and the large spread in the data. Our results are in a good agreement with previous results to within observational error: ~ 5 nT (Richardson, Cane, and Cliver, 2002), ~ 4.6 nT

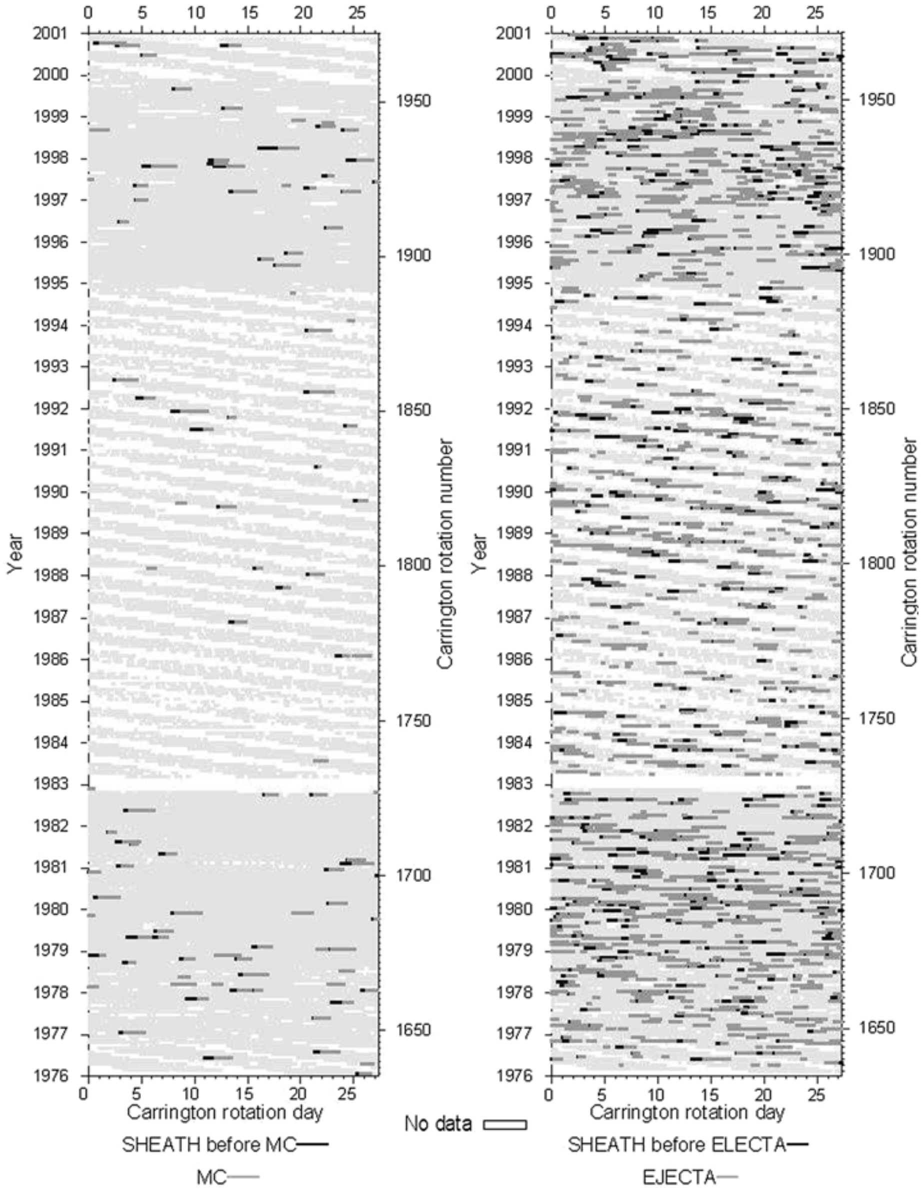

Figure 1 Temporal distribution of MC + sheath (left panel) and ejecta + sheath (right panel) observations during 1976 – 2000 (Yermolaev *et al.*, 2010).

(Svalgaard and Cliver, 2007) and 4.0 ± 0.3 nT (Owens *et al.*, 2008a). Our result was obtained for solar cycles 21 and 22 does not contradict the result 4.0 ± 0.3 nT (Owens *et al.*, 2008a) obtained for the end of solar cycle 23 and the hypothesis that the floor in IMF may decrease in cycle 23 (McCracken, 2007; Owens *et al.*, 2008a).

Our preliminary estimates show that the influence of the ICME contributions on the total IMF was sufficiently slight (in good accordance with previous data (Richardson, Cane, and

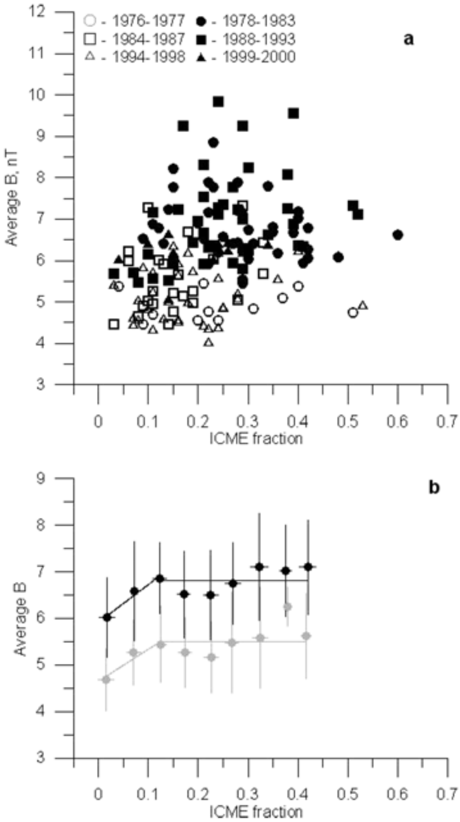

Figure 2 Dependence of the average magnetic field *B* on the ICME fraction: (a) two Carrington rotation averages for different phases of the solar cycle, (b) average over the ICME fraction bins for a maximum (black line) and a minimum (gray line) of the solar cycle.

Cliver, 2002)) and may be not enough to explain the increase in total IMF during maxima of the solar activity. A slight influence of the ICME contributions on the total IMF may be connected with interaction of ICMEs and local magnetic reconnection and annihilation of the ICME magnetic field during a large ICME occurrence rate.

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