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Minimum Value of the Heliospheric Magnetic Field in 2008–2010, According to WIND and ACE Data

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Abstract—Estimates are presented for the contribution from the magnetic fields of corotating regions of the interaction between fluxes of fast and slow wind to the measured heliospheric magnetic field (HMF) at 1 AU in the solar activity minimum of 2008–2010. A technique allowing such estimates to be made is considered, and the results from estimates made using data from the WIND and ACE spacecraft are presented. The contribution from the magnetic fields of corotating regions of interaction to the total field in the minimum of the 24th solar activity cycle is around 10%, and the minimum HMF intensity near the Earth in 2009 is 3.54 ± 0.11 nT. The magnetic fields of corotating regions of interaction play an important part in the modulation of galactic cosmic rays (GCRs). These fields affect HMF fluctuation spectra in the sector zone, altering the rigidity dependence of the GCR diffusion tensor and ultimately the GCR spectra in the heliosphere at particle energies of $E < 10$ GeV.

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INTRODUCTION

The heliospheric magnetic field (HMF) near the Earth changes strongly during every 11-year solar cycle, but the field magnitude in every solar cycle minimum returns approximately to the same low basic (“floor”) value. The estimate of the HMF magnitude of 4.6 nT in periods of minima was first obtained in [1] using various data (including geomagnetic data) for 150 years; magnetic fields were estimated for time intervals when there were no solar spots (the “no-sunspot floor”). The series of geomagnetic data was later extended to the past (to 1835), and the value B = 4.13 nT was presented in [2] for the minimum of 2009. In that minimum, solar activity was extremely low; as a result, the question arose of re-estimating the minimum floor level of the field. A new value of the minimum HMF intensity was obtained in [3]: 4.0 ± 0.3 nT. The authors of [3] proceeded from the assumption that the HMF consists of a constant component (the open flux component) and a time-variable field of coronal mass ejections (CMEs). The new value of the floor intensity minimum was obtained after excluding the contribution from magnetic fields from CMEs to the total magnetic field.

In this work, it is assumed that the HMF consists of the field of the open magnetic flux, magnetic fields of CMEs, and magnetic fields of corotating regions of the interaction between fast and slow wind fluxes. We assume that magnetic fields of corotating interaction regions (CIRs) form beyond the solar corona and the source surface situated at a distance of two or three radii from the Sun. The magnetic field within the CIR limits is generated directly in the heliosphere; it is not convected out from the corona as if it were frozen in plasma. CIRs are well bounded in the space and time, and their magnetic fields are easy to exclude from experimental data. We can then determine the minimum HMF intensity without the contribution from CIRs.

The technique allowing us to determine the contribution from CIR magnetic fields to the mean value of the measured HMF is based on their association with solar wind velocity V, temperature T, and proton density n in heliospheric plasma [4, 5]. To develop this technique, we used data obtained for the magnetic field and parameters of heliospheric plasma on board the Ulysses spacecraft. The plasma and magnetic field at the orbit of the Ulysses spacecraft are less complex than near the Earth, and relations between the CIR magnetic fields and plasma parameters are easier to establish.

RELATION BETWEEN THE HMF AND THE PARAMETERS OF HELIOSPHERIC PLASMA

Figure 1 shows HMF strength B and solar wind velocity V for January–April 1993 using hourly data of the Ulysses spacecraft. At that time, Ulysses moved to the South Pole of the Sun and was situated at a distance of 5.07–4.77 AU from it, at the southern heli-

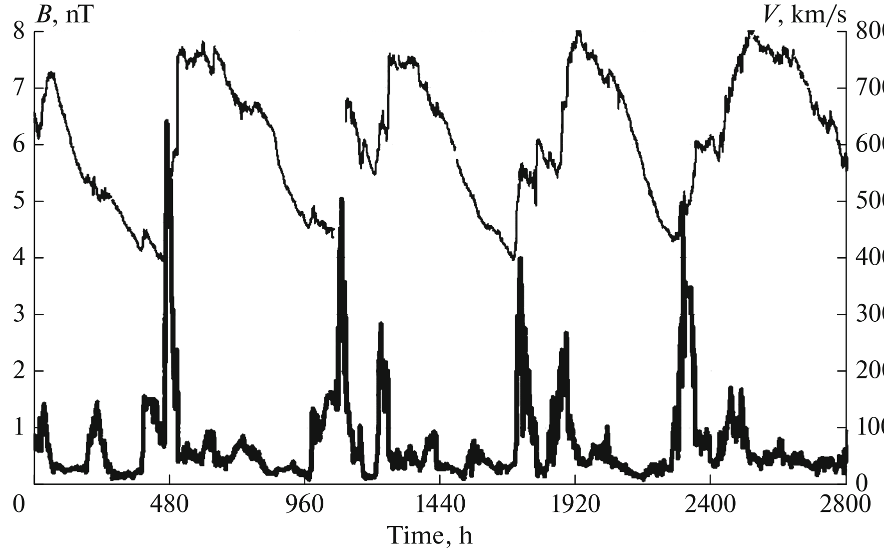

Fig. 1. Solar wind velocity V (thin line) and HMF intensity B (thick line), according to the Ulysses spacecraft data for January–April 1993. Time on the abscissa is measured in hours from the beginning of the year.

olatitude of 22.8°–29.8°. As is seen from Fig. 1, the correlation between B and V is low, and the coefficient of correlation between these quantities is $R = 0.168$. Despite the low correlation, however, the IMF strength is extremely sensitive to variations of the solar wind velocity. We can see that each front of a high-velocity solar wind flux is associated with a peak in IMF strength, and even small increases in the velocity lead to the formation of peaks in the magnetic field. The high-magnitude magnetic peaks in Fig. 1 are related to CIRs whose duration, as is shown below, fits exactly into the time interval coinciding with the duration of the front edge of the fast wind flow.

Figure 2a shows the proton density and temperature according to the Ulysses spacecraft's hourly data, along with the solar wind velocity in the first CIR in 1993 (January 20–22). The radial velocity of CIRs in the frame of reference associated with the Sun exceeds 400 km s^{-1}; the velocity of the Ulysses spacecraft is around 15 km s^{-1}. The Ulysses spacecraft may therefore be considered an immobile object the CIR passes by, regardless of whether Ulysses approaches the Sun or moves away from it.

Upon encountering a CIR, Ulysses registers the parameters of the plasma and magnetic field on the outer (antisolar) CIR side (the 460th hour from the beginning of the year). In this process, fast and short growth of proton density n and relatively small growth of temperature T are observed (Fig. 2a), along with an increase in magnetic field strength B shown in Fig. 2b. The increase in B is apparently due to simple plasma compression (as in the formation of super-strong magnetic fields during the fast compression of a current coil).

The central part of the CIR then passes by the spacecraft, i.e., the region of interaction between two plasma volumes whose magnetic fields are connected by field lines with two spatially different field sources on the Sun's surface. This is the so-called heated and decelerated flow of the high-speed solar wind [6]. In the interaction region, the slow wind magnetic field is detached from the source (with the formation of a tangential discontinuity). In the frame of reference moving with the CIR velocity, the forward wave (from the Sun) and reverse wave (toward the Sun) go out from the interaction region. In the region of the reverse wave (484th–508th hours) and at the reverse wave front (on the inner, sunward CIR side), the plasma temperature remains high, $T = 600000–500000$ K. The high plasma temperature maintains the higher field strength B.

At the 508th hour, Ulysses goes out of the CIR and into the flow of the fast undisturbed wind. Behind the reverse wave front, the proton density and magnetic field intensity drop abruptly. The proton temperature also falls sharply to values of ~150000–120000 K, and remains at this level for ~15 days.

Figure 2b, in addition to the measured HMF B (Ulysses), shows the magnetic field calculated with the formula $B_{calc} = B_0 + Kn\sqrt{T}$. The representation of the HMF as a function of local plasma parameters—density n and temperature T—was successfully used to describe the magnetic fields along the orbit of the Ulysses spacecraft and near the Earth [4, 5]. The formula for B_{calc} includes additional field B_0, depending on the radial distance from the Sun. Field B_0 determined from the experiment is 0.2 nT for the Ulysses spacecraft at 5 AU and 2.0 nT for describing the HMF near the Earth in the solar activity minimum.

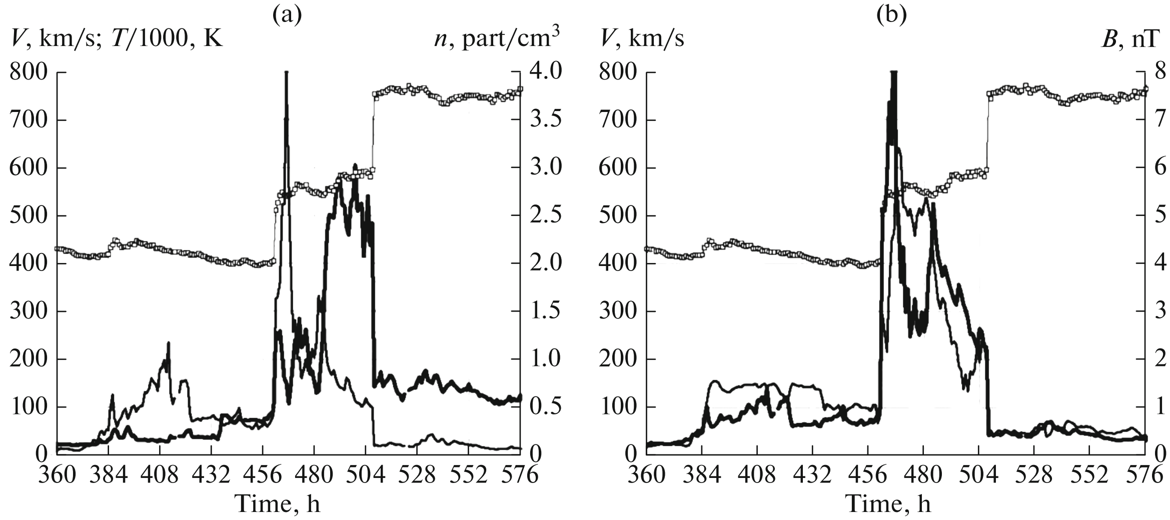

Fig. 2. Solar wind velocity V, temperature T, proton density n, and magnetic field intensity in the CIR detected by the Ulysses spacecraft in the period January 20–22, 1993. (a) Velocity V (white squares), temperature T (bold line), and proton density n (fine line). (b) Velocity V (white squares), HMF B(Ulysses) (fine line), and calculated magnetic field B_{calc} (bold line). Time on the abscissa is measured in hours from the beginning of the year.

We have thus shown that the CIR is bounded by the fast increase of the proton density on its outer side (Fig. 2a, the 460th hour) and by the equally fast drop in the proton temperature behind the reverse wave front (Fig. 2b, the 508th hour). The increase of the density coincides with that of velocity V at ~140 km s^{-1} for up to 1 h. The wind velocity then grows smoothly to ~600 km s^{-1}, followed by the second increase of the velocity. This is associated with the transition of the spacecraft to the fast wind region (about 750 km s^{-1}) and coincides in time with the drop in the proton temperature. The duration of the magnetic peak related to the CIR coincides sufficiently good with the time interval during which velocity V varies from 400 to 750 km s^{-1}.

To exclude magnetic fields of CIRs from the total data array, it is sufficient to exclude data in the time interval from the fast icrease in the proton density on the outer side of CIRs to the fast drop in the proton temperature behind the reverse wave front. In the example considered above, we should exclude the data for 48 h, from the 460th to the 508th hour. This approach was used to form “no CIR” arrays of data on the magnetic field in 2008–2010.

ACE AND WIND DATA ON PLASMA AND HMF IN THE MINIMUM OF THE 24th CYCLE

Hourly data from the ACE and WIND satellites in 2008–2010 [7] were considered to determine the basic HMF strength at 1 AU in the solar activity minimum of the 24th cycle. Both satellites were at Lagrange point $L1$, so their data on plasma and HMF should be similar. Comparison of hourly data from ACE and WIND on n, T, and B shows that they are almost identical, and no random noise fluctuations are observed in the hourly data. WIND data arrays with fewer gaps were therefore chosen for further calculations.

In calculating the HMF strength, WIND hourly data for 2008–2010 were divided into three-month arrays. For each array, mean strength $\langle B\rangle$ and average value $\langle B_{min}\rangle$ were calculated without the contribution from the magnetic fields of CIRs. The calculation results are presented below in Table 1. The annual average values of $\langle B\rangle$ are 4.21 ± 0.15 and 3.83 ± 0.11 nT for 2008 and 2009, respectively. The annual average values of $\langle B_{min}\rangle$ are 3.75 ± 0.07 and 3.54 ± 0.11 nT for 2008 and 2009, respectively. The contribution from the magnetic fields from CIRs to the total field near the Earth in the minimum of the 24th cycle was approximately 10%.

Table 1. HMF strength for 2008–2010 at 1 AU

Year	Months	$\langle B_{min}\rangle$, nT	$\langle B\rangle$, nT
2008	Jan–Mar	3.80	4.41
	Apr–Jun	3.81	4.24
	Jul–Sep	3.73	4.14
	Oct–Dec	3.65	4.05
2009	Jan–Mar	3.67	3.92
	Apr–Jun	3.50	3.68
	Jul–Sep	3.56	3.88
	Oct–Dec	3.42	3.85
2010	Jan–Mar	4.76	4.95

CONCLUSIONS

This work describes a data selection method that allows us to determine the HMF strength without the contribution from the magnetic fields of CIRs. Magnetic field $\langle B_{\min} \rangle$ at 1 AU, calculated using this technique in the period of the solar activity minimum of the 24th cycle, can be considered the minimum basic field determined by the solar magnetic field. Heliospheric magnetic field $\langle B_{\min} \rangle$ at 1 AU without the contribution from the magnetic fields of CIRs is 3.54 ± 0.11 nT for 2009. The contribution from the magnetic fields of CIRs to the total field in the minimum of the 24th cycle was approximately 10%.

The magnetic fields of CIRs, the contribution from which to the mean HMF is considerable in itself, play an important part in GCR modulation. The magnetic fields of CIRs alter the HMF fluctuation spectra in the sector zone, which changes the dependence of GCR diffusion on particle rigidity, and ultimately the GCR spectrum in the heliosphere at particle energies of $E <$ 10 GeV [8].

The authors of [1–3] are supporters of the view that the HMF is the sum of different fields: the field of the open magnetic flux (the open flux component) from the source surface and the magnetic fields of CMEs. The heliospheric magnetic field, which is determined by the open magnetic flux and detected in periods of solar activity minima, does not change during the solar cycle, and the magnetic fields of CMEs are merely superimposed on this field and produce its 11-year variation [1]. We treat the total HMF near the heliospheric current sheet as the sum of the three fields—the field of the open magnetic flux and magnetic fields of CMEs and CIRs.

We expected that $\langle B_{\min} \rangle$ would be approximately equal to additional field B_0 contained in the expression $B_{\text{calc}} = Kn\sqrt{T} + B_0$, however, this was not the case. The magnitude of additional field B_0 near the Earth in the minimum of 2009 was 2 nT; the minimum IMF value was 3.54 ± 0.11 nT.

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