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Does the solar wind affect the solar cycle?

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Abstract. We calculated the change of the magnetic flux through the surface encircled by the Earth's orbit. This change is associated with the magnetic flux transfer by the solar wind flow and exhibits clear 22-year periodicity. The magnetic flux transferred by the solar wind is of the same order of magnitude as the flux of the main solar magnetic field through the northern hemisphere of the Sun. There seems to be a feedback between the solar wind and the solar magnetism.

Key words: Sun: activity – Sun: magnetic fields – Sun: solar wind

1. Introduction

The main solar magnetic field demonstrates clear 22-year periodicity: at the beginning of the cycle (near the activity minimum), the magnetic field is predominantly dipolar, and the dipole is almost aligned with the Sun's rotation axis. The relative role of higher harmonics (quadrupole, octupole, etc.) increases with solar activity, resulting in total destruction of the initial regular dipolar magnetic field configuration after 5–6 years, near the solar maximum. On the decline phase of the solar cycle, the dipole field is restored with the opposite direction of the dipole. Thus, the main solar magnetic field becomes predominantly dipolar again (being rotated by 180 °) after approximately 11 years. During the subsequent 11 years the dipole performs the next turn and arrives at the initial configuration (e.g. Babcock 1961).

This cycle is accompanied by variations of signatures of solar activity like sunspots, solar flares and coronal mass ejections. Obviously, the solar wind parameters are also affected by changing initial/boundary conditions of its outflow in the solar atmosphere. The dependence of the solar wind spatial/temporal structure on the solar magnetic field is investigated in a number of papers (e.g., King 1979, Slavin et al. 1984, 1986; Winterhalter et al. 1990, McComas et al. 1992, Neugebauer et al. 1998). However, it remains obscure whether a feedback exists between the solar wind and the solar magnetism. In other words, does the solar wind affect the solar cycle?

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There are at least two reasons to ask this question. First, the magnetic field produced by the heliospheric current system is not negligibly small near the Sun and, hence, it may be necessary to take it into consideration in the problem of solar magnetic field generation. Indeed, the magnetic field, produced near the Sun by the heliospheric current sheet, can be estimated as

$$B_0 = \frac{2\pi}{c} \int_{R_0}^{\infty} \frac{i_\varphi(r)dr}{r},$$

where i_φ is the azimuthal component of the electric current surface density in the sheet, and $R_0 \approx 3R_\odot$ is the distance at which the current sheet starts. The electric current surface density is $i_\varphi = cB_r/2\pi$, where B_r is the radial component of IMF above (or below) the current sheet. Since $B_r \propto 1/r^2$ and equals $\sim 3 \times 10^{-5}$ G at 1 AU, $B_0 \approx 0.07$ G, i.e. several percent of the global solar intrinsic magnetic field.

The second reason, which we believe to be more important and which we will address in this note is as follows. It is not clear in advance, that the interplanetary electric field (IEF) associated with the solar wind plasma flow $\mathbf{E}_{SW} = -1/c[\mathbf{v}_{SW} \times \mathbf{B}_{SW}]$ is a potential field. Of course, the instantaneous values of $\nabla \times \mathbf{E}_{SW}$ may be non zero because of the variability of the solar wind. Discussing the potentiality of the IEF, we mean $\mathbf{E}_{SW}$ values averaged over time scales larger than the period of the Sun's rotation (but much smaller than the solar cycle period). Usually, in modeling it is implicitly assumed that $\oint \mathbf{E}_{SW} d\mathbf{l} = 0$ which means that the solar wind plasma flows along the IMF lines (in the frame of reference rotating with the Sun) (e.g. Pneumann & Kopp 1971, Cuperman et al. 1990, Linker et al. 1996). We will check the validity of this assumption using the available data on the long term solar wind monitoring.

2. Results

A near-Earth spacecraft encircles the Sun each 27 days in the frame of reference rotating with the Sun. The spacecraft data on $\mathbf{v}_{SW} \times \mathbf{B}_{SW}$ integrated over this period may be used in order to estimate the circulation $\oint \mathbf{E}_{SW} d\mathbf{l}$ over the Earth's orbit. It is important to note that the circulation calculated in the rotating non-inertial frame of reference will remain the same in the inertial frame. We used the data on the IMF and on the solar

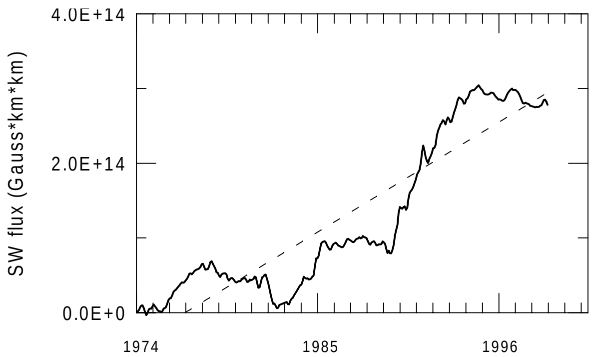

Fig. 1. Magnetic flux transferred by the solar wind through the Earth's orbit. Dashed line is a linear fit.

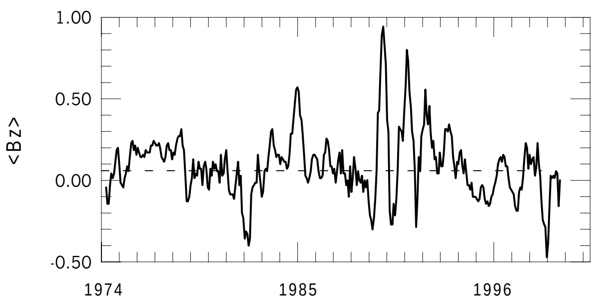

Fig. 2. Averaged per solar rotation the northward component of the interplanetary magnetic field B_z at R = 1 au. Solid line shows the sliding average over seven solar rotations, dashed line corresponds to the B_z averaged over the whole period of observations (i.e. systematic shift δb).

wind velocity available from National Space Science Data Center (http://nssdc,gsfc.nasa.gov/omniweb). Since the data series are not continuous (there were certain periods when $\mathbf{v}_{SW}$ and/or $\mathbf{B}_{SW}$ have not been measured), the circulation of the IEF was calculated as follows. First, we found the average value of the φ-component of the IEF for each Carrington rotation using all the data available for this rotation. Then, the circulation of the IEF for this rotation was estimated as $\oint \mathbf{E}_{SW} d\mathbf{l} = 2\pi a \langle E_\varphi \rangle$, where a is the radius of the Earth's orbit. Afterwards, by integrating Maxwell's equation

$$\oint \mathbf{E}_{SW} d\mathbf{l} = -\frac{1}{c}\frac{\partial}{\partial t}\int\int \mathbf{B} d\mathbf{s},$$

we calculated how the total magnetic flux through the surface encircled by the Earth's orbit changes with time starting from 1974, January 1. The results are shown in Fig. 1. One can see clear 11-year variability on the background of the strong linear trend shown by dotted line. However, this trend seems not to have physical sense. Indeed, if there is a small systematic shift δb in the values of the B_z-component of the IMF, then the integration of the quantity $v_{SW} \cdot \delta b$ will result in the linear trend. Taking the average value of $v_{SW} = 450\,\mathrm{km\,s^{-1}}$, we estimate that the observed trend due to δb is as small as 0.06 nT. It should be noted that the data at the OmniSpace set are rounded to the accuracy of 0.1 nT. The value of B_z averaged over the whole period of observation (0.06 nT) is smaller than the quantization

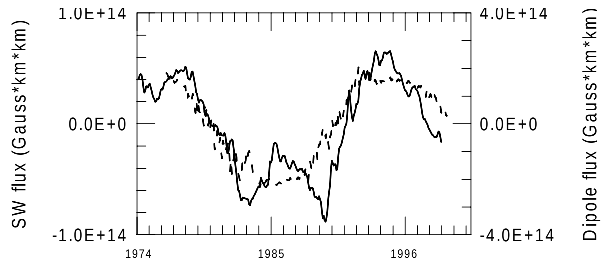

Fig. 3. Solid line shows the change of the magnetic flux (due to the solar wind flow) through the surface encircled by the Earth's orbit. Dotted line corresponds to the solar main dipole magnetic field flux through the northern hemisphere of the Sun.

of data and, hence, should be neglected. On the other hand, the presence of this small systematic shift results, after integration, in linear trend seen in Fig. 1. The 11-years variations of the calculated magnetic flux are primarily associated with the values of B_z averaged over one solar rotation. These values are shown in Fig. 2 (solid line) and appear to be an order of magnitude larger than the systematic shift (dashed line). Thus, the linear trend is an artifact due to the rounding of the data, and it should be subtracted from the calculated magnetic flux in order to obtain the magnetic flux transferred through the Earth's orbit. Below, we will also check this statement using data sets with higher (0.01 nT) resolution for the IMF.

The magnetic flux transferred through the Earth's orbit is shown in Fig. 3. Dashed line in the same Fig. 3 shows the temporal behaviour of the magnetic flux associated with the dipolar component of the main solar magnetic field through the Sun's northern hemisphere. This quantity was calculated by using the solar magnetic field Gaussian harmonic coefficients at Wilcox Solar Observatory (http://quake.stanford.edu/∼wso). The resemblance between the two curves is noteworthy. Not only the temporal profiles of the two quantities are similar, but the absolute values of the magnetic fluxes are very close: the magnetic flux change associated with the solar wind flow is only ~ 3 times smaller than the flux of the main solar magnetic field.

In principle, there is some probability that the coincidence is accidental. One can try to explain it by means of solar-cycle-driven periodicities in solar wind parameters. In this sense, the most suspicious possibility is as follows. The average solar wind velocity varies with the phases of the solar cycle. If some systematic shift δb is present in the IMF B_z-component (and this is so, indeed, as one can see from the linear trend in Fig. 1, discussed above), then the quantity $\oint(\mathbf{v}_{SW} \times \delta\mathbf{b})d\mathbf{l}$ may be responsible for the magnetic flux changes shown in Fig. 3. We checked this possibility, and the results are shown in Fig. 4. Solid line here shows the change of the magnetic flux through the surface encircled by the Earth's orbit (same as in Fig. 3). Dashed line represents the integral $\int_{1974}^{t}\oint(\mathbf{v}_{SW} \times \delta\mathbf{b})d\mathbf{l}dt$ This value appears to be ten times smaller than the quantity of interest and has quite different temporal profile. Thus, the magnetic flux change shown in Fig. 3, most probably, is associated with the solar wind flow.

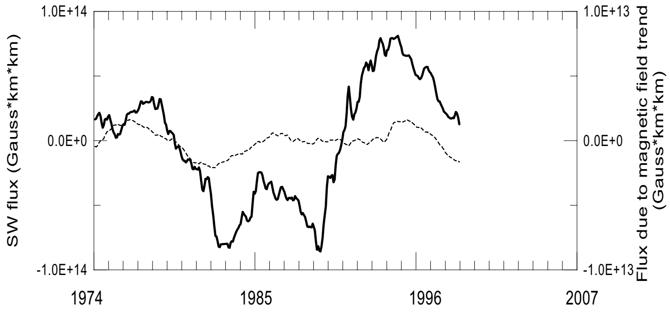

Fig. 4. Change of the magnetic flux through the surface encircled by the Earth's orbit (solid line) and the value $\int_{1974}^{t} \oint (\mathbf{v}_{SW} \times \delta\mathbf{b}) d\mathbf{l} dt$ (dotted line).

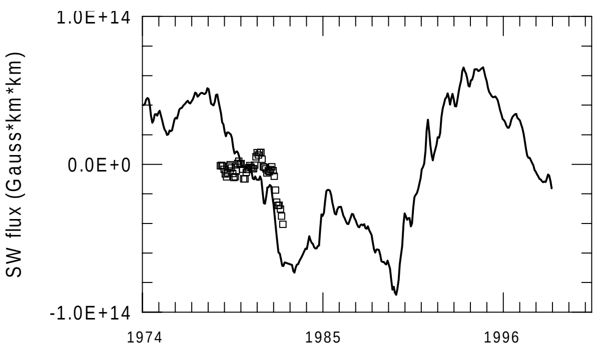

Fig. 5. Magnetic flux transferred through the Earth's orbit calculated from OMNI data (solid line, same as in Fig. 3) and from ISEE-3 measurements (empty squares).

Fig. 3 compares the solar dipole magnetic flux with the magnetic flux transferred through the Earth's orbit as observed during 1974–1999 by a number of satellites orbiting the Earth (IMP 1–8: Explorer 33, 35; HEOS 1 and 2, VELA 3; OGO 5; ISEE 1 and 2; PROGNOZ 10; and Wind). The independent verification can be performed using the observations of magnetic flux transfer by the interplanetary spacecraft. In order to make this check possible, (a) the data row from a spacecraft should be long enough (at least five years) in order to be comparable with solar periodicities; (b) a spacecraft should orbit the Sun close to the ecliptic plane; (c) the distance of the spacecraft to the Sun should not vary significantly. Three missions satisfy these conditions: Helios-1 (1974–1980), ISEE-3 (1978–1982), and Pioneer-Venus (1979–1988). We applied the same procedure in order to calculate the magnetic flux transferred through the orbits of these spacecrafts.

Fig. 5 shows the results for ISEE-3 data (empty squares) with near-Earth measurements (solid line). The behaviour of the curves and the magnitude of the transferred flux are rather similar for these two independent sets of data. Fig. 6 compares near-Earth measurements (solid line) with the results for Helios-1 (empty circles) and for Pioneer-Venus (black dots). Again, the temporal profiles of three independent measurements of magnetic flux transfer are the same. However, the magnitude of the magnetic flux transferred through the Helios and Pioner-Venus orbits is twice larger than that for the Earth orbit. Note, that the

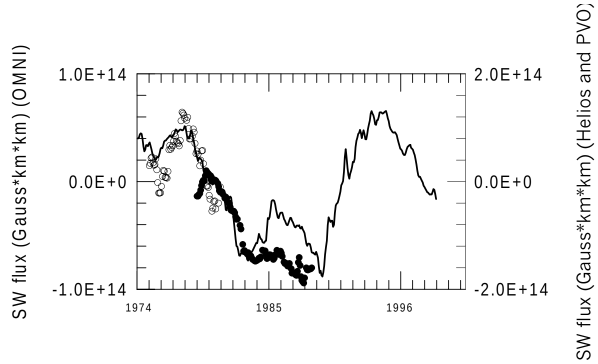

Fig. 6. Magnetic flux transferred through the Earth's orbit calculated from OMNI data (solid line, same as in Fig. 3) and magnetic flux transferred through the Helios 1 (empty circles) and Venus (dark dots) orbits.

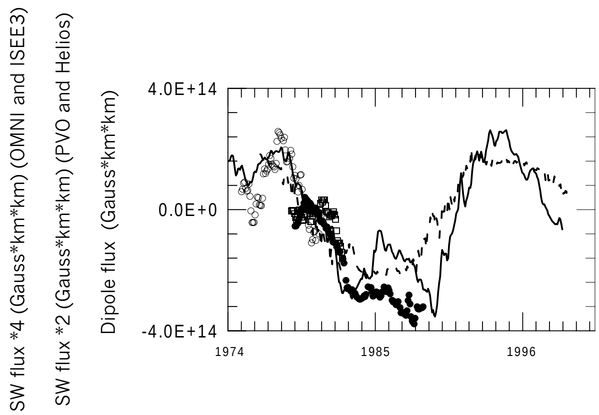

Fig. 7. Solar main dipole magnetic field flux through the northern hemisphere of the Sun (dashed line), and magnetic field flux convected with the solar wind calculated from OMNI data set (solid line), ISEE-3 (empty squares), Helios 1 (empty circles) and PVO (dark dots) data.

data for ISEE-3, Helios-1 and Pioner-Venus, whose accuracy is 0.01 nT, does not exhibit significant linear trend. This fact justifies our above statement that the linear trend in Fig. 1 is an artifact of data rounding.

Fig. 7 combines all the available results: solid line corresponds to the flux through the Earth's orbit (OMNI data set); empty cirles, empty squares and black dots correspond to Helios-1, ISEE-3 and Pioner-Venus data, respectively; and dashed line shows the changes in solar magnetic dipole flux. All independent sets reveal the same temporal behaviour. The difference in magnitude of the magnetic fluxes may be explained as follows. Solar dipole magnetic flux (dashed lines in Figs. 3 and 7) was calculated for the whole northern hemisphere of the Sun. As can be seen from Fig. 8, the magnetic flux transferred through the orbit at the distance R from the Sun, corresponds to the change of the magnetic flux through a polar part of the Sun's hemisphere. The equatorward boundary of this polar cap corresponds to the magnetic field lines (shown by thick lines in Fig. 8) which cross the equator at the distance R to the Sun. Thus, the magnetic flux transfer observed by the spacecraft should be smaller as the spacecraft distance from the Sun increases. This is indeed true for our data sets. Same values of the magnetic

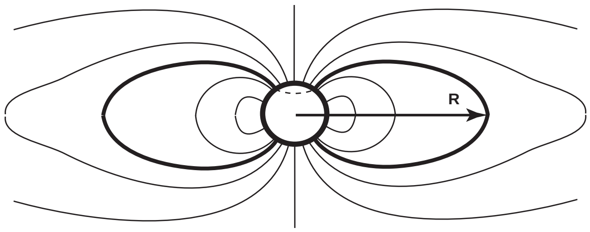

Fig. 8. Cartoon of the interplanetary magnetic field lines. Thick lines show the field lines crossing the equatorial plane at the distance R. The change of the magnetic flux through the circle of radius R in the equatorial plane is equal to the change of the magnetic flux through the polar region of the solar surface encircled by the dashed line.

flux are obtained for ISEE-3 and OMNI set ($R = 1$ au), and for Pioner-Venus ($R = 0.72$ au) and Helios-1 (average $R = 0.69$ au), whereas Pioneer-Venus/Helios fluxes are twice larger than OMNI/ISEE-3 fluxes. The dipole magnetic flux through the polar region with the boundary at the colatitude θ is proportional to $1 - \cos 2\theta$. For our relation between solar dipole flux and transferred fluxes, one estimates that the Earth's orbit corresponds to the solar latitude of 55^0, and the Venus' orbit coresponds to the solar latitude of 35^0. However, one should be cautious with these estimates because of uncertainties in measurements of the main solar magnetic field.

3. Conclusion

We have shown that significant amount of the solar magnetic flux is convected with the solar wind. As a result, the change of the magnetic flux through the surface encircled by the Earth's orbit (or the Venus' orbit) is proportional to the flux of the main solar magnetic field through the northern hemisphere of the Sun. During the solar cycle approximately one quarter of the total solar magnetic flux is transferred through the Earth's orbit (one half through the Venus' orbit). It means that the solar magnetic field is convected polarward destroying the dipolar structure and resulting in appearance of higher harmonics. Hence, the solar wind plasma flow plays significant role in the generation of the global solar magnetic field, and, in particular, may be responsible for the overturning of the solar dipole each 11 years.

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References

Babcock H.W., 1961, ApJ 133, 572
Cuperman S., Ofman L., Dryer M., 1990, ApJ 350, 846
King J.H., 1979, J. Geophys. Res. 84, 5938
McComas D.J., Gosling J.T., Phillips J. L., 1992, J. Geophys. Res. 97, 171
Linker J.A., Mikic Z., Schnack D.D., 1996, In: Balasubramaniam K.S., Keil S.L., Smartt R.N. (eds.) Solar Drivers of Interplanetary and Terrestrial Disturbances. ASP Conf. 95, San Francisco, p. 208
Neugebauer M., Forsyth R.J., Galvin A.B., et al., 1998, J. Geophys. Res. 103, 14587
Pneumann G.W., Kopp R.A., 1971, Solar Phys. 18, 258
Slavin J.A., Smith E.J., Thomas B.T., 1984, Geophys. Res. Lett. 11, 279
Slavin J.A., Jungmann G., Smith E.J. 1986, Geophys. Res. Lett. 13, 531
Winterhalter D.E., Smith E.J., Wolfe J.H., 1990, J. Geophys. Res. 95, 1