

Relation of cyclic variations of the solar wind and interplanetary magnetic field to the cycles of solar magnetic fields

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Abstract. Annual mean values of dynamical parameters of the solar wind and interplanetary magnetic field during 1964–1996 and the errors of their determination were obtained from the data of the King catalogue electron version presented on the Internet. The 11-year cycles of all characteristics of the interplanetary plasma and their relation to cycles of various solar magnetic fields were analyzed from them. Using this analysis, the difference in cycles of various characteristics of the interplanetary medium is demonstrated. Attention is paid to systematic discrepancies in cycling variations of the plasma density before and after the beginning of the 1970s and to nonadequacy of variations of the initial interplanetary magnetic field vector to variations of its components.

1. Introduction

The current knowledge on plasma flows from the Sun (these flows will below be called solar wind, the definition being broader than the *Parker* [1976] definition which referred to the plasma flow related only to the corona hydrodynamical expansion into the interplanetary space: quiet solar wind with a velocity of $\sim 300 \text{ km s}^{-1}$) shows that the flows are rather complicated formations which are influenced by the variations of the large-scale solar magnetic fields including the cyclic variation with $T \approx 11$ years. The variation of the annual dynamical parameters of the solar wind (SW) and also “frozen” into it interplanetary magnetic field (IMF, B_I) are below analyzed from these positions. The relation (different for different parameters) between the cyclic variations of the solar magnetic fields and interplanetary medium parameters is demonstrated, and some features of the experimental data in the King catalogue which complicate their analysis are indicated.

2. Dynamical Parameters of the Plasma

The initial and smoothed annual values of three dynamical parameters of solar wind (the velocity V , density n , and momentum nV) calculated for 1964–1996 from the data of the King catalogue (<http://nssdc.gsfc.nasa.gov/omniweb>) and *Rivin* [1989] are shown in Figure 1a. The annual parameters and their root mean square error (σ) were determined in the calculation, the smoothing being performed with a running interval ($L = 3$ years). Figure 1a shows the errors only for the initial curve of the solar wind velocity. Their average value for the entire temporal interval is $\langle \sigma \rangle \approx \pm 10 \text{ km s}^{-1}$; this value is almost by a factor of 1.5 higher in 1986–1996 than earlier during 1964–1985. The values of σ for the plasma density has smaller representation scale ($\langle \sigma \rangle \sim 0.5 \text{ cm}^{-3}$ and slightly changes in the entire temporal interval).

The comparison of the momentum variations with the velocity and density variations shown in Figure 1a and also the analyzes of the dependencies $nV(t) = f(V)$, $nV(t) = f(n)$ shown in Figure 2 make it possible to conclude that the cyclic variations of nV are not an independent characteristic since they are determined mainly by the cyclic variations of the plasma density:

$$d(nV)/dt = n(dV/dt) + V(dn/dt) \approx Vdn/dt \quad (1)$$

where $V \approx \text{const}$, and in the following consideration the main attention should be paid only to analyzes of V and n .

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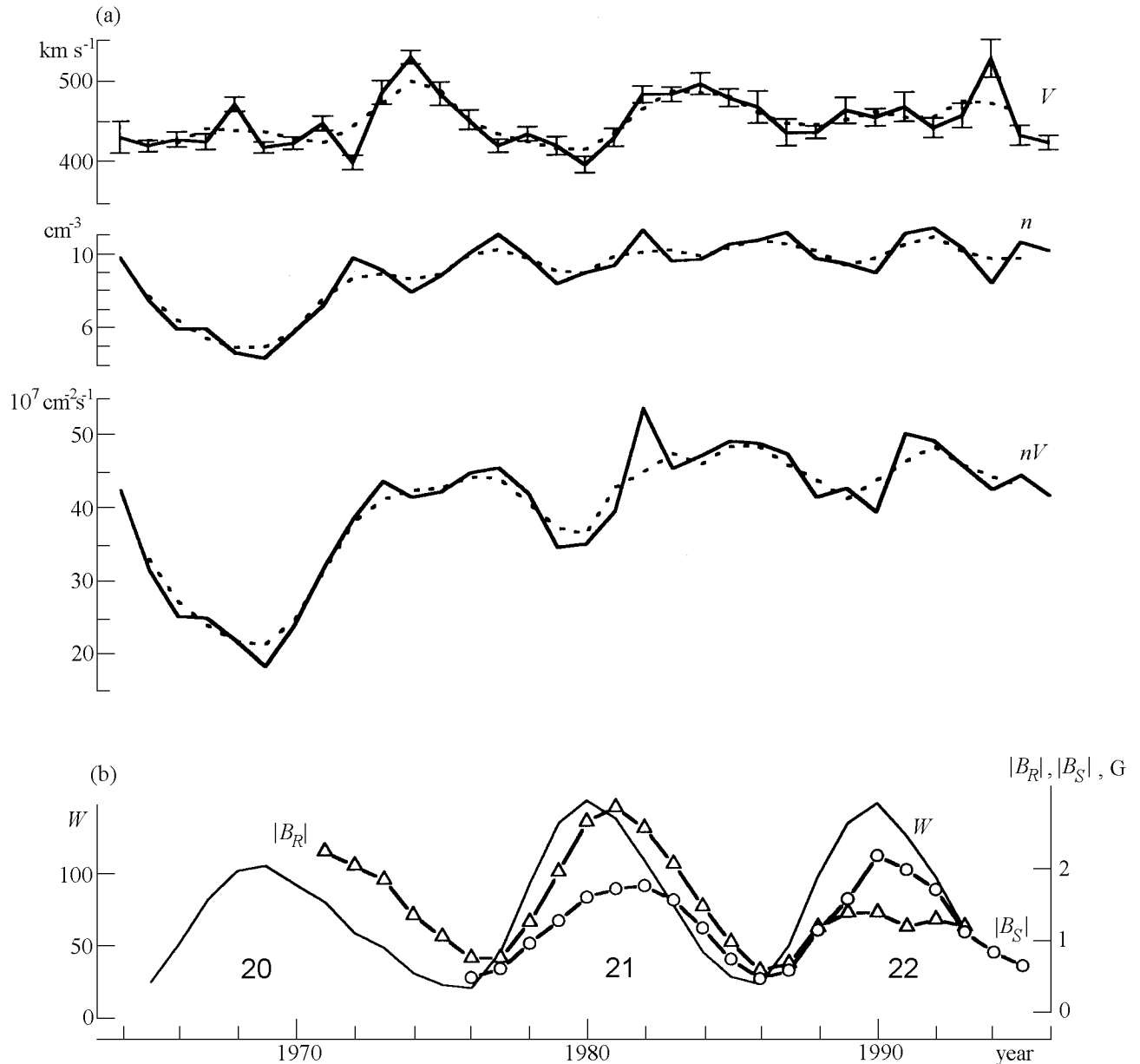


Figure 1. (a) Initial (solid line) and smoothed (circles) annual mean values of three dynamic parameters of SW and (b) smoothed annual mean values of the solar magnetic fields (the values of $|B_S|$ should be multiplied by 0.25), see the text. Vertical lines show the errors of annual mean determination.

Figure 3 shows the spectra of three dynamical parameters of the plasma. They were obtained by an expansion of the curves in Figure 1a into Fourier series with fractional harmonics. The harmonic with $T \approx 10 - 11$ years is quite visually (in comparison with other harmonics) seen in the spectrum of V , the spectra of n and nV are distorted by the lower-frequency (than the cycle) variation which may be related to the variations of these two parameters before the

beginning of the 1970s (Figure 1a). Its exclusion (by shortening of the series expanded into spectrum) shows presence of a harmonic with $T \approx 11$ years (which is visually seen in the initial data (Figure 1a)) in the variations of these two parameters. The nature of the trend in curve n is not probably related to cyclisity, that fact being discussed below.

Figure 1b shows (smoothed by the same L) curves of the annual values of: (1) the Wolf numbers (W) as the character-

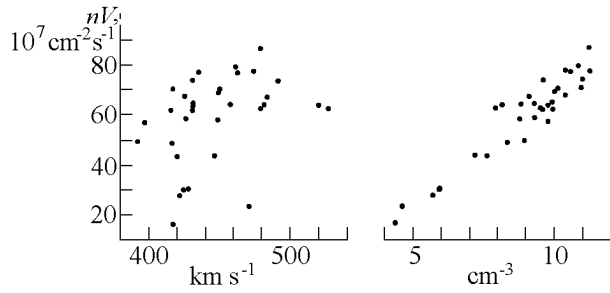


Figure 2. Dependence of nV on n and V .

istic of the cyclic variation of the toroidal component of the solar magnetic field 1B generated above the basic of the convective zone, and (2) the magnitude of the radial component of the large-scale magnetic field $|B_R|$, 2B generated within the basis of the convective zone, and the field of the Sun as a star $|B_s|$ which plays a determining role in processes in the interplanetary medium. *Obridko and Rivin* [1996] and *Rivin* [1998a, 1998b, 1999a, 1999b] discussed these characteristics in detail and called the former and latter fields dipole and quadrupole, respectively. A complete comparison of the cycles of these magnetic fields with the interplanetary medium parameters is difficult because of the short series of observations (2–3 cycles). However to distinguish cycles of various fields, the difference in their amplitude modulation was taken into account: for $|B_R|$ the amplitude of cycle 22 is several times lower than the amplitude of cycle 21, for W and $|B_s|$ the amplitudes in both cycles are approximately equal, or the amplitude of $|B_s|$ is even slightly higher in cycle 22. These differences and also the phase variations are used in the interpretation below.

The comparison of cyclic variations of V and n with the cycles of the large-scale solar magnetic fields was carried out on the correlation plane (Figure 4) and by calculation of inter-correlation function $r(t)$ (Figure 5). Taking into account the spectra in Figure 3, one can derive the following conclusions from this comparison:

1. In the main dynamical parameters of SW there exists a ~ 11 -year cycle which is mainly in antiphase to the cyclic variations of $|B_R|$. Its amplitude decreases in n and V from cycle 20 to cycle 22 and the spectral amplitude exceeds by several times the amplitudes of other harmonics including the harmonics with $T \approx 22$ years.

2. The cycle with $T \approx 11$ years in the data on V is additionally shifted in phase by 2–3 years (it lags) relative the cycle of $|B_R|$, that is, by ~ 3 –4 years relative to the W cycle. Its spectral amplitude for 3 cycles is ~ 20 km s $^{-1}$ and that is only slightly higher than $\langle \sigma \rangle$.

3. The properties of the ~ 11 -year cycle in n till the beginning of the 1970s are considerably different from the properties of the following two cycles (on the $n - W$ plane in Figure 3 the data for the years before the beginning of the 1970s form such a point distribution which is approximated by a straight line having essentially different coefficients than those for the following cycles). That requires individual consideration of this parameter before and after the years indi-

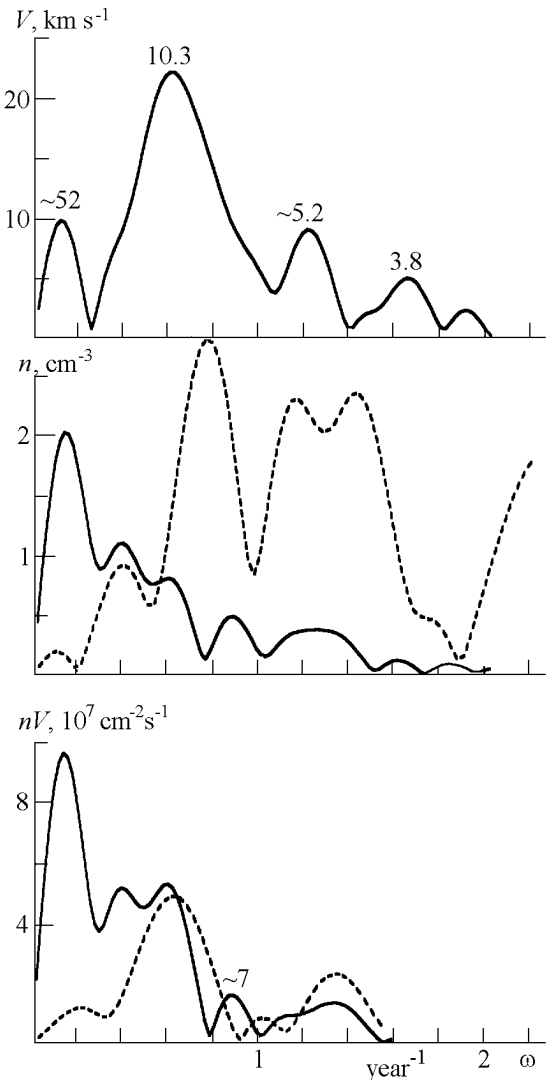


Figure 3. Fourier spectra of the annual values of the dynamical parameters of SW for 1964–1996. The dashed line shows the spectra for 1971–1996. Numerals at the harmonic maxima are periods in years.

cated. It is possible that this difference is the cause of the distortion of the n and nV spectra in Figure 3. The cycle of the plasma density according to the data from 1971 (practically after the doubtful interval) occurs strictly in antiphase to the $|B_R|$ cycle without any delays. Its approximate average amplitude is 0.5 – 1 cm $^{-3}$ that is close to $\langle \sigma \rangle$ as in case of the SW velocity.

Hence some properties of the n and V cycles (properties 1–3) correspond to the properties of the cycles of the 2B magnetic field. However, it is possible that the correlation is still more informative at the $n - W$ plane than at the $n - |B_R|$ plane.

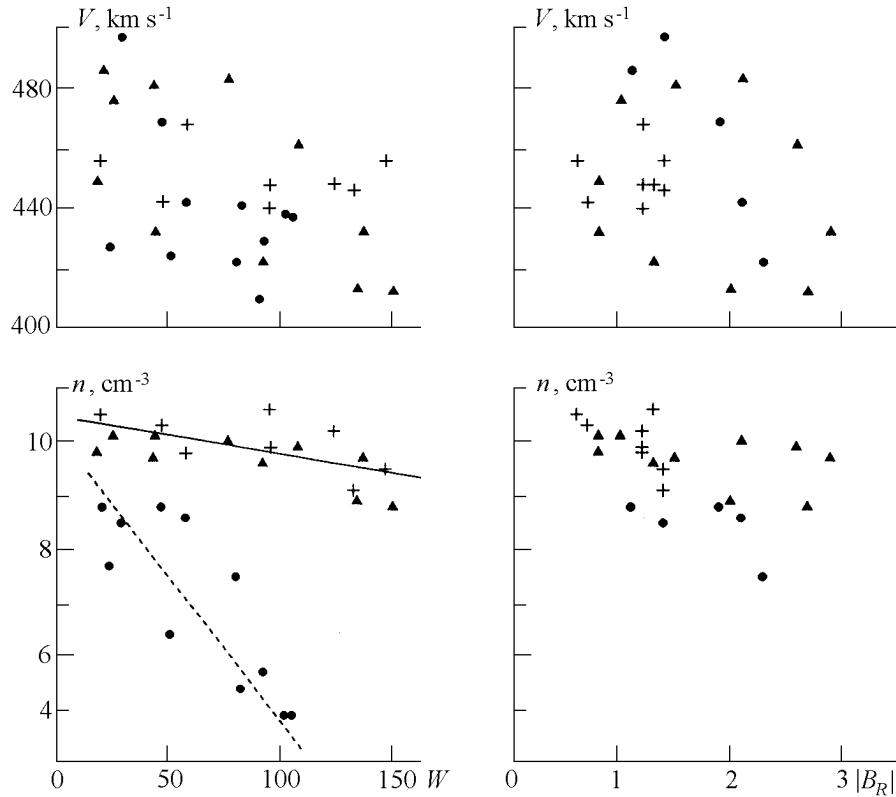


Figure 4. Dependence of the SW dynamical parameters on (left) W and (right) $|B_R|$ in Gs on the correlation plane for three solar activity cycles: 20 (circles), 21 (triangles), and 22 (crosses). The approximating distributions of circles in various cycles are shown by solid and dashed lines on the $n - W$ plane.

3. Interplanetary Magnetic Field

More than 30 years ago *Severnyy* [1966] suggested that the interplanetary magnetic field is a continuation of the total magnetic field of the Sun B_s into the interplanetary space and proposed observations of this solar field as a field of a star for diagnostics of IMF variations. The modern experimental data on the $|B_z|$ and $|B_s|$ 11-year cycles support this suggestion.

Figure 6 shows the initial and smoothed by the L interval annual values of the vector of the interplanetary magnetic field B_I and its three orthogonal components B_x , B_y , and B_z . Comparing variations of the latter with the former makes it possible to conclude that there is no coordination in their occurrence: the vector variations demonstrate the 11-year cyclisity, such cyclisity being absent in the components. At the same time, the B_I variations agree well with the modulus values of the vector and the component module (Figure 7). Also the variations of the B_y and B_x components (particularly the former which occur in phase with the IMF variations and so may be used as an analog of the initial IMF variations near the Earth) are well correlated with the vari-

ation of the total magnetic field of the Sun which is shown at the bottom of Figure 6.

Figure 7 shows variations of the modules of the IMF vector and components and also variations of the solar magnetic fields. Here the identity of the variations of the vector and its components with the variations of $|B_s|$ is already visually seen.

Figure 8 shows the results of consideration of the relation between $|B_I|$ and $|B_s|$ on the correlation plane separately for each cycle. The adjacent points are connected by line, and the arrows and dates show the motion direction in time. The absence of phase shifts between two fields is seen even from this figure. The linear approximation of this distribution results in a high correlation coefficient ($r = 0.95 \pm 0.06$) and a regression equation $|B_I| = (5.2 \pm 0.15) + (6.02 \pm 0.46) \times 10^{-5} |B_s|$, where $|B_I|$ is in nT and $|B_s|$ is in Gs ($1 \text{ Gs} = 10^5 \text{ nT}$). The following conclusions were derived from the analysis performed:

1. The amplitude attenuation of the cyclic variation of the modulus of the total magnetic field of the Sun near the Earth is a factor of $\sim 2 \times 10^4$.
2. The amplitude of the ~ 11 -year cycle of IMF increases from cycle 20 to cycle 22 and is approximately equal in cycles

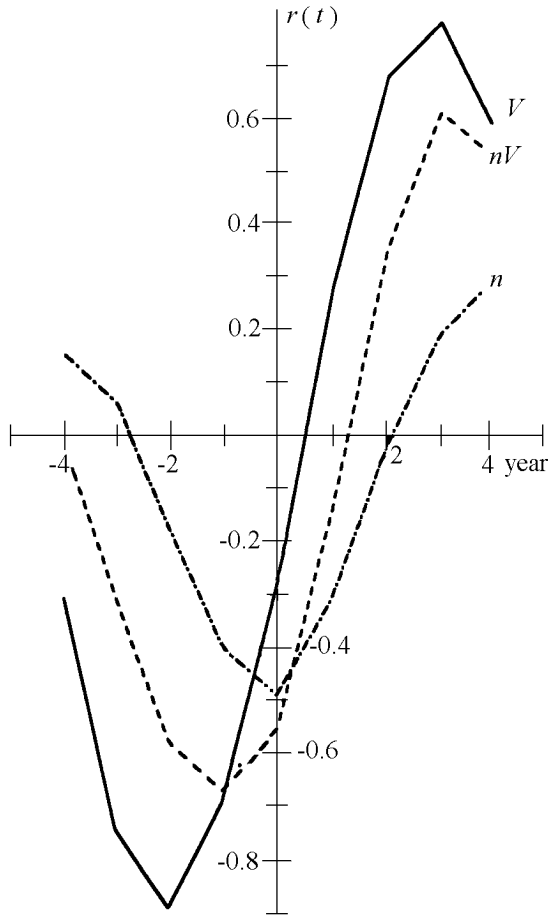


Figure 5. Determination of the dependence of the phase shift of the V , n , and nV cycles on the phase of the $|B_R|$ cycle with the help of the intercorrelation function from the data after 1971.

21 and 22 (even is slightly higher in the latter), this fact being principally different from the amplitude modulation of the V and n cycles.

3. No phase shifts between the $|B_I|$ and $|B_s|$ cycles were discovered.

4. The cyclic variation of the modulus of the total magnetic field of the Sun (B_s) is the main source of the cyclic variation of IMF.

5. The variations of the initial annual values of B_I and its components do not contain explicitly expressed cyclisity with $T \approx 11 - 22$ years. The best correlation is detected between the phase of the total solar magnetic field variation with the B_y component of the interplanetary magnetic field.

6. The scatter of points relative the approximating line in Figure 8 has a tendency to be lower in the middle part of the cycle and to increase in the epochs of its extremes.

4. Discussion

The cyclic variation of $|B_s|$ contains a superposition of the $|^1B|$ and $|^2B|$ magnetic fields; the $|^1B_s|$ input prevails in the amplitude variations and the $|^2B_s|$ input is manifested in the phase shift of the $|B_s|$ cycle relative the W cycle by 1–2 years [Rivin, 1998b, 1999a, 1999b]. The corresponding properties of the cyclisity of the solar magnetic fields are “inherited” by the modulus of the interplanetary magnetic field, that is, the variations of $|B_I|$ with $T \approx 11$ years are on the whole identical to similar variations of $|B_s|$. At the same time the variations of the B_y and B_x (the latter in antiphase) components of the initial IMF correspond to the variations of B_s .

It is principally important and in some way unexpected that the cyclic variations of the two main dynamic parameters of SW, probably first, differ from the variations of $|B_I|$ and, second, have somewhat different properties: the phase of the V cycle is shifted by ~ 3 year relative the phase of the W cycle, whereas the phase of the n cycle coincides with the phase of the $|^2B_s|$ magnetic field cycle. Probably, this difference indicates similar but slightly different formation sources of the cycles of these two parameters. At the same time the amplitude attenuation of the cycles of both parameters shows that probably the field $|^2B_s|$ influences each of them more than the $|^1B_s|$ field, that is, the plasma has a much deeper origin.

Annual mean values of n before the early 1970s are systematically underestimated by $3-4 \text{ cm}^{-3}$. It follows from the “ $n - W$ ” plot (Figure 4) that this underestimation is not caused by random errors. It is not yet clear whether it manifests a systematic error in the n determination in King catalogue for the corresponding year or has some physical sense. The results of this paper correct partially the assumptions (made by Rivin [1989] earlier) on the cyclisity nature of the interplanetary medium parameters varying with $T \approx 11$ years.

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References

- Obridko, V. N., and Yu. R. Rivin, Magnetic field in the near-equatorial solar photosphere, *Astron. Zh. (in Russian)*, 73, 812, 1996.
- Parker, E. N., Basic mechanisms of solar activity, in *Proceedings of the Symposium 71 IAU, Prague, August 1975*, edited by V. Bumba and I. Klechek, D. Reidel, Norwell, Mass., 1976.
- Rivin, Yu. R., *Earth's and Sun's Cycles (in Russian)*, 165 pp., Nauka, Moscow, 1989.

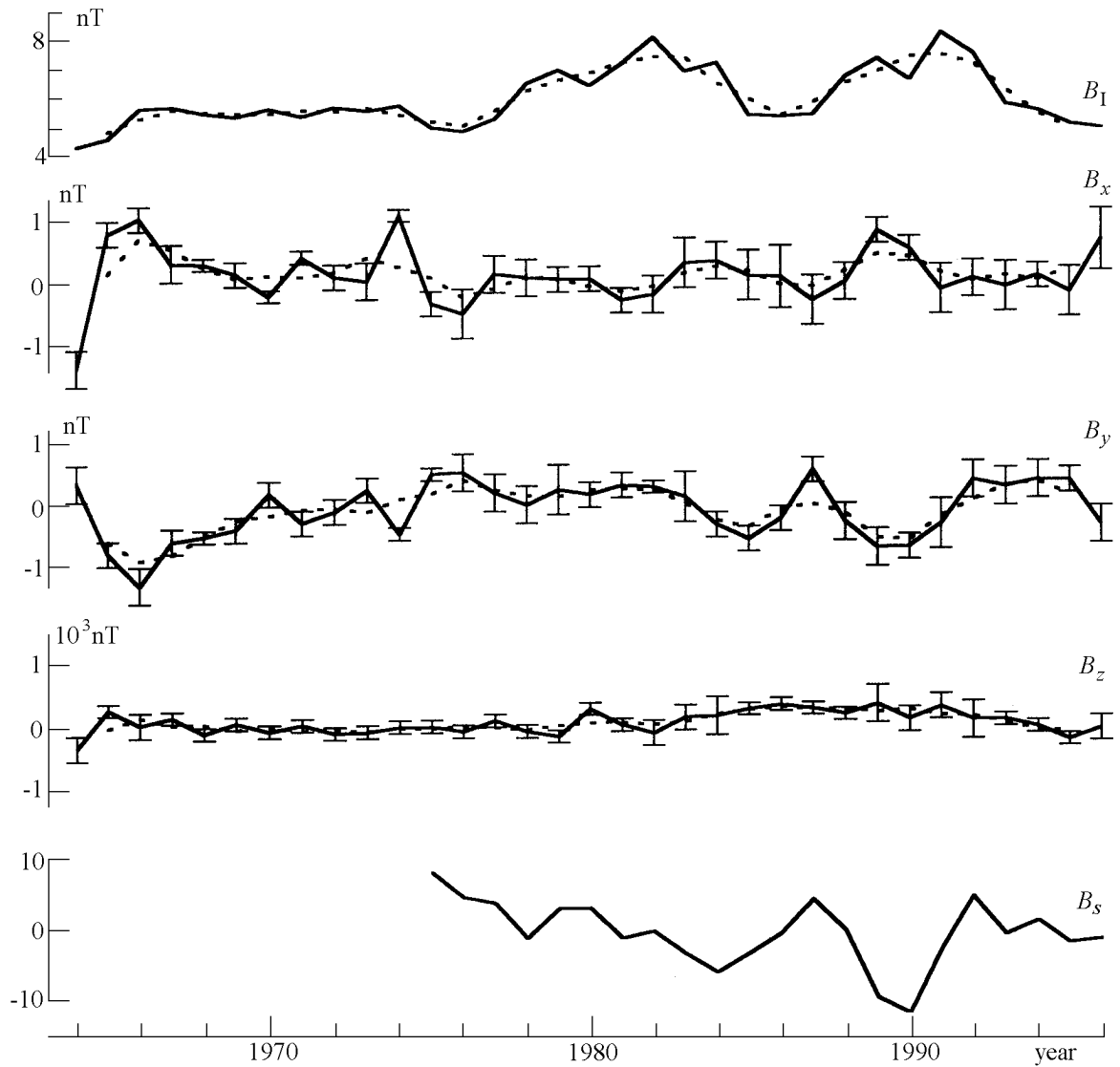


Figure 6. Initial and smoothed (solid and dashed lines, respectively) annual means of the total vector of the interplanetary magnetic field $|B_I|$ and its three orthogonal components. Vertical lines show the errors of annual mean determination. Curve B_I is the total vector calculated from the annual mean values of the components. Variations of total magnetic field of the Sun as a star are shown at the bottom.

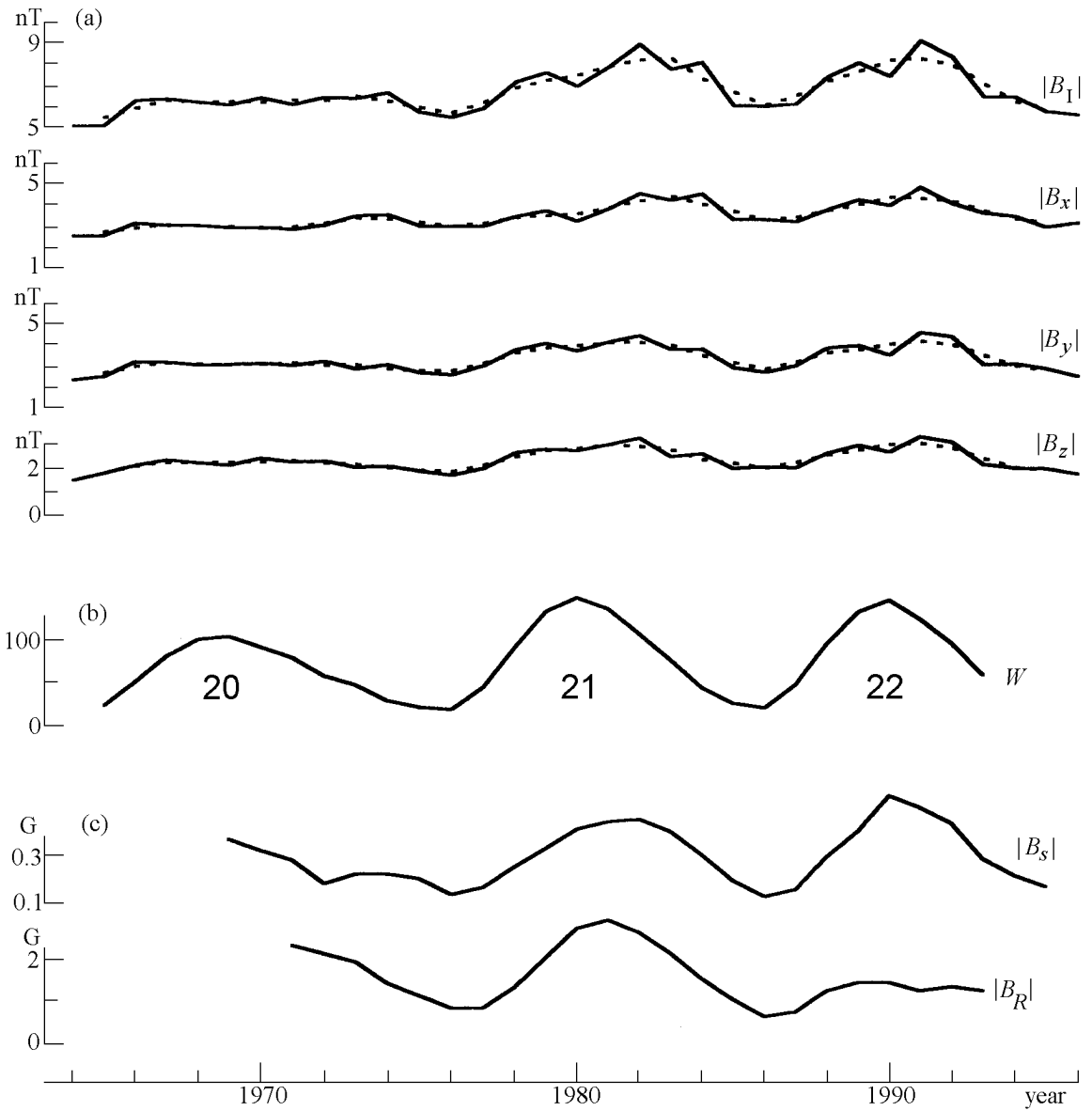


Figure 7. (a) Modulus of the IMF vector and its components, (b) the Wolf numbers, and (c) modulus of the solar magnetic fields. Numerals at the Wolf numbers are the numbers of the 11-year cycles of W .

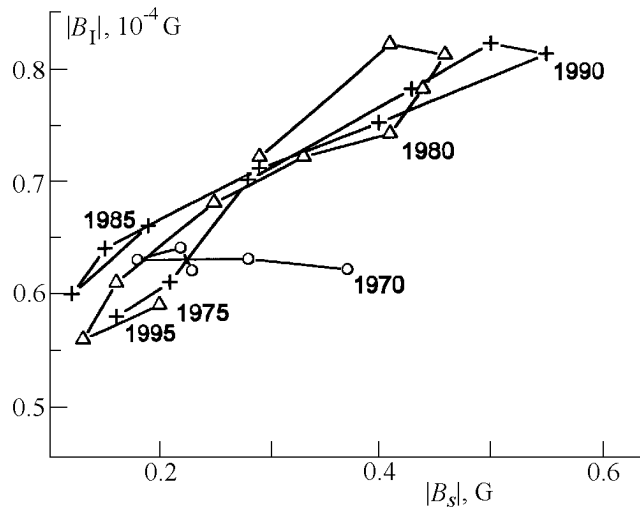


Figure 8. Relation between $|B_I|$ and $|B_s|$ at the correlation plane for incomplete three solar cycles: 20 (circles), 21 (triangles), and 22 (crosses). $|B_s|$ in cycle 20 is taken from the data of the Crimean Astronomical Observatory.

Rivin, Yu. R., Specification of the analytical model of the cyclic variations of the magnetic fields at middle and low latitudes of the Sun, *Izv. Akad. Nauk Ross. Ser. Fiz. (in Russian)*, 63, 1263, 1998a.

Rivin, Yu. R., Principal construction elements of the mechanism of cyclic changes generation in large-scale and local solar magnetic fields, *Izv. Akad. Nauk Ross. Ser. Fiz. (in Russian)*, 63, 1867, 1998b.

Rivin, Yu. R., Principal contradiction between the experimental data on solar activity cyclisity and current theoretical models of its description, *Pis'ma Astron. Zh. (in Russian)*, 25(4), 314, 1999a.

Rivin, Yu. R., 11-year cycles of the low-latitude large-scale solar magnetic field, its origin and sources in the convection zone, *Sol. Phys.*, 187, 207, 1999b.

Severnnyy, A. B., Magnetic fields of the Sun and stars, *Usp. Fiz. Nauk (in Russian)*, 88, 3, 1966.

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