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Multiparameter Computations of Solar Wind Characteristics in the Near-Earth Space from the Data on the Solar Magnetic Field

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Abstract—The solar wind parameters were analyzed using the concept which is being developed by the authors and assumes the existence of several systems of magnetic fields of different scales on the Sun. It was demonstrated that the simplest model with one source surface and a radial expansion does not describe the characteristics of the quiet solar wind adequately. Different magnetic field subsystems on the Sun affect the characteristics of the solar wind plasma in a different way, even changing the sign of correlation. New multiparameter schemes were developed to compute the velocity and the magnetic field components of the solar wind. The radial component of the magnetic field in the solar corona and the tilt of the heliospheric current sheet, which determines the degree of divergence of field lines in the heliosphere, were taken into account when calculating the magnetic field in the solar wind. Both the divergence of field lines in the corona and the strength of the solar magnetic field are allowed for in calculating the solar wind speed. The suggested schemes provide a considerably higher computation accuracy than that given by commonly used one-parameter models.

INTRODUCTION

Biermann (1951, 1957) was the first to indicate in the early 1950s a continuous gas flow from the Sun with velocities from 500 to 1500 km/s. Parker (1958) was one of the first to develop this idea using a mathematical apparatus. He introduced the magnetic field into a solar wind (SW) model and concluded that the solar radial magnetic field is stretched by the gas flow; twisting strongly and changing its strength, the field reaches the interplanetary space and generates the interplanetary magnetic field. On average, if the flow runs out quietly, the solar radial magnetic field must reduce proportionally to r^{-2} in the interplanetary space. After the number of observations increased and their quality improved, especially after launches of numerous geophysical satellites, it became clear that the relationships between the solar magnetic fields and the solar wind parameters are very complex and considerably depend on time.

The following step in the problem of calculating the interplanetary magnetic field from the solar magnetic field parameters was a development of the computation method applying the so-called source surface (Altschuler and Newkirk, 1969; Shatten *et al.*, 1969; Hoeksema and Scherrer, 1986; Wang and Sheeley, 1992). In fact, this was an attempt to pass to direct computations using actual solar magnetograph observations of the magnetic field on the photospheric surface. In toto, the results proved to be encouraging, the signs of B_x (the radial component of the interplanetary magnetic field near the Earth) and B_{ss} (the magnetic field on the source surface) agree well (with allowance for the four-day transport time). However, the value of B_x calculated from the standard r^{-2} expansion law turned out to be much less than that measured directly (Obridko *et al.*, 1996). Attempts to improve the situation by modifying the computation scheme (by applying the concept that the field is radial within the photosphere, by shifting the height of the source surface, by introducing two source surfaces, see below) were not successful.

The situation with calculating the solar wind speed is also complicated. It was found long ago that an average solar wind speed is about 400 km/s, but no method has been developed so far to calculate actual daily mean or even monthly mean speeds from the solar data. Good progress was made by Wang and Sheeley (1990, 1991), who introduced a new parameter (a factor of divergence of the solar magnetic field f_s determined by the ratio of the fields on the photosphere and on the source surface at points connected by a field line) and calculated the solar wind speed with the use of this parameter. The introduction of this parameter was based on theoretical investigations of matter outflow from coronal holes, in which the divergence factor is determining. However, when the results of calculating daily mean values were analyzed for the whole solar surface, they were found to be not very promising, with low correlation coefficients. Then, the authors divided the entire observed range of solar wind speeds into four subranges depending on the divergence factor. No noticeable improvement of correlation between the solar magnetic field and the solar wind speed was found in each subrange. In this case, the aforementioned authors also did not succeed in getting high correlation coefficients in continuous calculations of monthly means, they achieved mean correlation coefficients (~0.4) for monthly mean values. The basic difficulty was in mixing up the points that should belong to different speed subranges according to the calculations of the divergence factor.

The results of Wang and Sheeley were revised by the authors of the present study (Obridko *et al.*, 1996). One more additional parameter was introduced—a turning point near B_{ph} = 750 G in curves splitting the speed range into subranges. This enhances the correlation by approximately 10%, but it was still low (<0.5). In the end of the paper, the authors came to the conclusion that the SW speed cannot be uniquely determined by solar magnetic fields. This can be caused by insufficient resolution used in observations of solar magnetic fields and by the source surface conception applied. To define the solar wind speed more accurately, Shelting and Obridko (1996) introduced another additional parameter-the length of the solar magnetic field line segment between the photosphere and the source surface *L*. In three-dimensional diagrams (V, f_s, L), the correlation enhanced considerably after the velocities had been partitioned in four subranges because particles with higher velocities naturally describe a shorter path between the photosphere and the source surface. Thus, the authors arrived at the conclusion that the relationship between the solar magnetic fields and the solar wind is complex and ambiguous and depends on many factors and solar–terrestrial parameters to different extents.

In the present work we again turned to the question about the relationship between characteristics of the solar magnetic field and of the solar wind and came to the conclusion that multiparameter models, which include solar magnetic fields of different scales (local and global) and solar wind parameters in different combinations, have the best prospects.

REMARKS ON BOUNDARY CONDITIONS

After regular magnetograph measurements of photospheric magnetic fields had started, several models were considered with the aim to calculate magnetic fields at some heights above the photosphere. The first such model suggested in the late 1970s was the model of potential field—the source surface—which is well-known and widely applied now (Altschuler and Newkirk, 1969; Shatten *et al.*, 1969; Hoeksema and Scherrer, 1986). The radius of the source surface was taken equal to $2.5R_0$. As a magnetograph measures the magnetic field along the line of sight and the radial component forms the boundary condition, some additional hypothesis about the field in the photosphere was needed. A natural assumption was considered that the hypothesis of potentiality is also true at the boundary photospheric surface. In this case one can calculate the longitudinal component with undetermined coefficients and, after comparing it with observations, solve the problem completely. This was realized in the above-cited papers. However, analyzing the WSO observations, Svalgaard *et al.* (1978) demonstrated than the dependence of a signal on the position of the observation point on the disk is the same as it should be in the case of a purely radial magnetic field along long distances. The point is that the potential approximation assumes that there are no currents in the medium. Obviously, this is not quite correct for the photosphere. In addition, the concept of kilogaussian tubes combined with an increased buoyancy of these tubes must also lead to an increase of the radial component of the magnetic field in the photosphere (Stenflo and Vogel, 1986). After numerous highly accurate data, particularly satellite images, appeared at the end of 1990s and they were compared to calculations, this lead to ideas that calculations by the model of potential longitudinal layer with the source surface at a height of $2.5R_0$ do not agree well with satellite data, especially in the interplanetary space. New models with small modifications of initial conditions were developed. In one of the most generally used models, of Wang and Sheeley (1992), the magnetic field on the photosphere is assumed to be radial (in accordance with the results of Svalgaard (1978)) and the height of the source surface corresponds to $3.25R_0$.

As our goal was to find the best correlation between the parameters of the magnetic field on the Sun and the heliospheric parameters, we decided that it is necessary to compare these two models in order to understand which one is better for our study. We based our comparison on observations of the longitudinal component of the magnetic field observed at the Wilcox Solar Observatory in Stanford obtained via the Internet.

Computations were made for the following four variants.

(1a, b). The field was assumed to be potential at the photospheric level. The source surface was at $R = 2.5$ or 3.25.

(2a, b). The field was assumed to be radial at the photospheric level. The source surface was at $R = 2.5$ or 3.25.

In each of the four variants we calculated all components of the magnetic field and some arbitrary indices at the levels of the photosphere and source surface. Of course, in the second case, we actually calculated the meridional and latitudinal components slightly above the photosphere.

It turned out that the field structure was nearly the same in all four cases. Comparing the fields calculated by models 1a and 2b for 1977–2001, we found that the coefficient of their correlation is very high and shows slight cyclic variations with minimal values at the minimum of the solar cycle (about 86%) and maximal values at its maximum (about 96%). In this case the coincidence was very good even for small features.

Thus, for the majority of problems, in particular for problems of cyclic evolution of large-scale fields, both concepts can be applied. A similar conclusion was made by Wibberenz *et al.* (2002) when they examined the role of the tilt of the heliospheric current sheet in modulation of cosmic rays.

DATA AND METHODS

To calculate solar parameters, in this paper we used low-resolution measurements of the large-scale magnetic field on the photosphere, obtained by a magnetograph at the Wilcox Solar Observatory in Stanford for the period from 1976 till now. The solar wind parameters were taken from the OMNIWeb; they were kindly provided by the National Space Science Data Center (NSSDC), Greenbelt, Maryland. We applied the following solar parameters: the magnetic field on the photosphere B_{ph}, the modeled magnetic field on the source surface B_{ss}, and the factor of the magnetic field divergence f_s. We also used the following interplanetary parameters: the solar wind velocity V, the interplanetary magnetic field B_m, and the magnetic field components B_x and B_y in the helioecliptic coordinate system. Daily mean values were taken for all parameters. Also semiannual and biannual moving averages were used to reveal the cyclic behavior.

The parameter of divergence of field lines in the potential region was calculated by the formula

$$f_0 \equiv \left(\frac{R_s}{R_0}\right)^2 \frac{B_r(R_s, \lambda_s, \phi_s)}{B_r(R_0, \lambda_0, \phi_0)}, \tag{1}$$

where the value of the magnetic field $B_r(R_s)$ is taken at the point of the Earth's helioprojection on the source surface (λ_s, ϕ_s) and the value of $B_r(R_0)$ is taken at the photospheric end of the same field line. The radius of the source surface was hereafter taken equal to $2.5R_0$. Note that this definition of the divergence parameter is the inverse of the parameter f_s introduced by Wang and Sheeley (1990, 1991)

$$f_0 \equiv 1/f_s. \tag{2}$$

When the magnetic field on the Sun is compared to the magnetic field near the Earth, the transport time, which is necessary for a perturbation from the Sun to pass a distance of one astronomical unit, is a very important parameter. Obviously, this time can vary considerably depending on the type of perturbation. However, taking into account such dependencies of the transport time for each event turns out to be a very complicated procedure when we deal with statistical calculations based on a great body of daily mean data referring mainly to rather quite solar wind. As a result, we adopted a constant value of the transport time equal to 4 days. It must naturally lead to some additional scatter of points in the diagrams and to lower correlation coefficients.

Another problem is that, according to the model of solar wind outflow, B_x (the component of the interplanetary magnetic field in the helioecliptic coordinate system) must be opposite in sign to B_{ss} (the magnetic field on the source surface) with allowance for the arrangement of axes. In fact, this law is violated for rather a great number of daily mean values (as much as in 30% in some years). The situation cannot be improved significantly by varying the transport time. This disagreement is obviously determined by the contribution of nonstationary processes not described by the simplest model of solar wind outflow or arises during the process of propagation in the interplanetary space as a result of flow interactions.

These two notes immediately impose restrictions on the expected correlations for daily means. It is clear at once that we should not expect correlation coefficients exceeding 0.6–0.7. In addition to the correlation coefficients, we also need to get a coincidence of mean calculated and measured strengths of the interplanetary magnetic field. It is not simple at all because the strength of the field depends on the Sun-to-Earth distance in quite an unclear way. At a sufficiently large distance, the r^{-2} law is probably satisfied. However, on an acceleration curve near the Sun this relation is already different, and thus the coefficients of correlation between B_{ss} and the interplanetary magnetic field can be determined by several parameters. In particular, this relation can also depend on characteristics of local fields and on the polar field, as it was demonstrated by Obridko *et al.* (2003).

COMPUTATION OF THE INTERPLANETARY MAGNETIC FIELD

We found correlations between the solar magnetic field and the most significant and interesting for us solar wind parameters. The whole time interval (25 years) in view was split into one-year subintervals. For each year the coefficients of univariate correlation between B_{ss} and B_x and B_y were found by the least-squares method using the first-degree polynomial fit.

As it was expected, the coefficients change from year to year. Figure 1 shows the temporal variations of the function of cross-correlation between the magnetic field on the source surface B_{ss} and the components of the interplanetary magnetic field B_x and B_y. The correlation between B_{ss} and the B_z component is very low. It is not surprising because B_z is evidently generated in the process of propagation in the interplanetary medium. The question of the origin of B_z is not considered in the present paper. The correlation between B_{ss} and the components B_x and B_y is much stronger. The coefficients of correlation between B_{ss} and B_x, B_y are close to each other and vary in an irregular way from 0.4 to 0.7 exhibiting some increase associated with growth and fall phases of solar activity cycles.

Although the coefficients of correlation are relatively high for daily mean values, there are some problems with the calculated values of B_x and B_y. If the coefficient of correlation between the field on the Sun and B_x is assumed to be proportional to r^{-2}, the values obtained turn out to be too small. That is why we introduced another approximation to calculate B_x and B_y. We use the same form of the formula approximating the dependence of $B_{x,y}$ on B_{ss}, but introduce the exponents $\alpha_{x,y}$ defined directly.

$$B_x = -B_{ss}\left(\frac{2.50}{210}\right)^{\alpha_x} \times 1000, \quad (3)$$

$$B_y = B_{ss}\left(\frac{2.50}{210}\right)^{\alpha_y} \times 1000. \quad (4)$$

The term in the brackets shows the ratio of the radius of the source sphere to the astronomical unit, and the multiplier 1000 indicates the difference in units of measure.

Using formulas (3) and (4) we can find the values of α for those days when the sign relation is satisfied and then calculate the annual mean values. These annual means are shown in Fig. 2.

It can be seen that the curves exhibit a clearly pronounced cyclic behavior with minimal values of about $\alpha_{x,y}$ = 1.35-1.4 at minima of solar activity (1977, 1986, 1996) and maximal values of about 1.7–1.75 at maxima of solar activity (1980, 1990, 2000).

One can see a noticeable resemblance of the temporal behavior of α and the Wolf numbers W. Figure 3 shows α_x and α_y as a function of W as well as their second-degree polynomial fits. The coefficients of cross-correlation are characterized by small scatter and large values; they are about 0.89 for α_x (0.894 for nonlinear correlation and 0.883 for linear correlation) and about 0.84 for α_y (0.843 for nonlinear correlation and 0.831 for linear correlation).

Probably, the correlation between the exponent α and the tilt of the heliospheric current sheet (tilt) is physically more significant. This relation is demonstrated in Fig. 4, and the regression equations and the coefficients of correlation ρ are given in the following formulas (5) and (6)

$$\alpha_x = 1.26951 + 0.433651 \sin(\text{tilt}), \quad \rho = 0.883, \quad (5)$$

$$\alpha_y = 1.29724 + 0.403628 \sin(\text{tilt}), \quad \rho = 0.825. \quad (6)$$

In this case the exponent α is determined by the divergence of the field lines, confined to the heliospheric current sheet, in the initial part of the acceleration path of the solar wind. At minimum, when the heliospheric current sheet is a plane, the field lines can spread only in the equatorial plane, and α is small and differs from unit only slightly. Closer to the maximum, the heliospheric current layer swings nearly to the pole and α increases approaching 2.0.

Thus, formulas (3)–(6) determine a general procedure of calculating the heliospheric magnetic field from the solar parameters. The measured and calculated temporal variations of B_x in 1991 are shown in Fig. 5. It can be seen that they agree quite well for the most part. Nearly all details in both curves coincide. Nevertheless, the values at some points are equally signed but differ by a factor of 1.5–2.

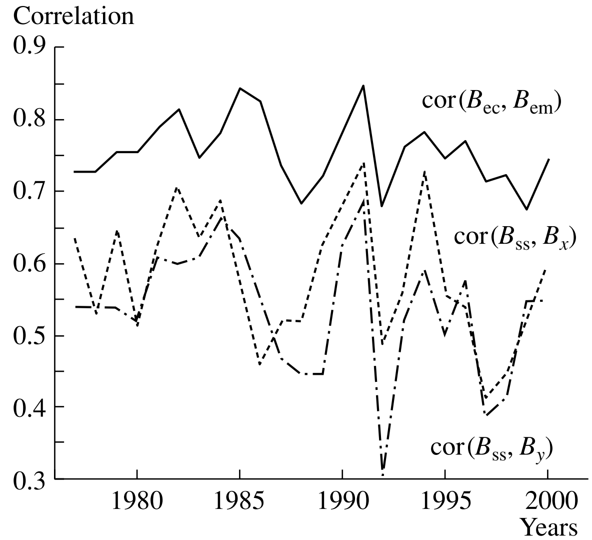

Fig. 1. Coefficients of correlation between B_{ss} and B_x (dashed line), B_{ss} and B_y (dot-and-dash line), and B_{ec} and B_{em} (thick solid curve) as a function of time.

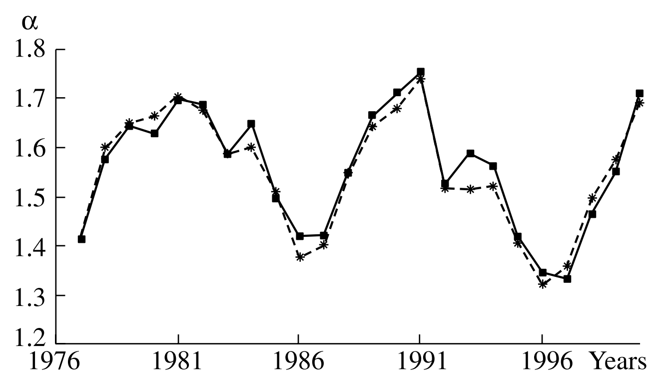

Fig. 2. The exponents α_x (solid line) and α_y (dashed line) versus time.

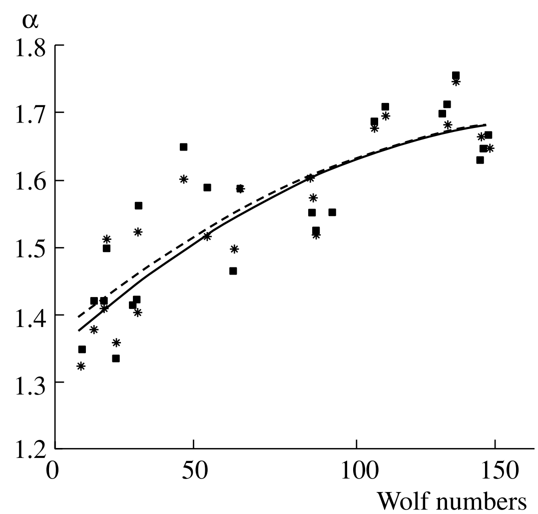

Fig. 3. The exponents α_x (stars and solid line) and α_y (circles and dashed line) as a function of the Wolf numbers.

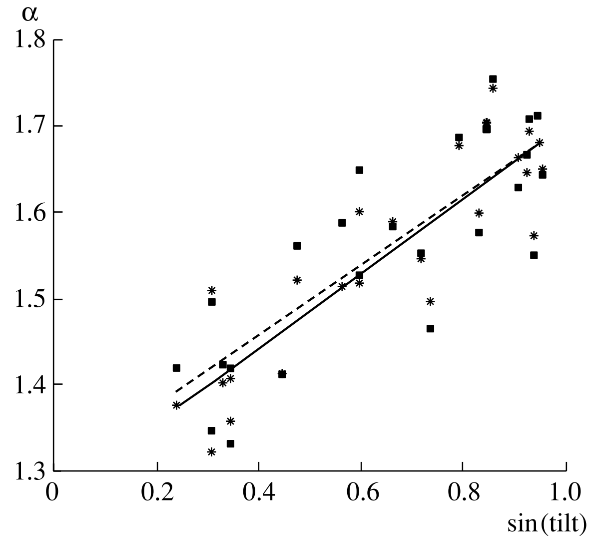

Fig. 4. The exponents α_x (stars and solid line) and α_y (circles and dashed line) as a function of the tilt of the heliospheric current sheet.

Since our computation scheme satisfactorily describes the components B_x and B_y of the interplanetary magnetic field, we can calculate the ecliptic component of the field $B_e = \sqrt{B_x^2 + B_y^2}$, which is used in some applications. In this case, in accordance with generally used procedures, we shall assign to B_e the sign of B_x. So the value of B_{ec} calculated by our model can be compared to B_{em} calculated from the directly measured components B_x and B_y. The coefficient of correlation of B_{ec} and B_{em} is shown by the top thick line in Fig. 1. It can be seen that the correlation became higher.

CALCULATION OF SOLAR WIND SPEED NEAR THE EARTH

The problem of calculating the near-Earth solar wind speed is rather more complicated than the problem of calculating the B_x and B_y components of the interplanetary magnetic field. This is, firstly, associated with the fact that the physical mechanisms linking the field on the Sun and in the heliosphere are principally understood better. At the same time, it is not clear enough which parameters on the Sun control the solar wind speed. We have only characteristics of the magnetic field at our disposal, but their relation to the speed can be highly indirect and probably nonlinear. In addition, the dynamical range of daily mean velocities is much narrower than that of B_x and B_y: the velocities change only by a factor of 1.5–2. This introduces additional difficulties to the selection of governing parameters.

These difficulties led to the fact that though the mean velocity varies little, the calculations of daily means in previous studies usually gave very low coefficients of correlation. As said in the Introduction, the parameter of divergence f_s suggested by Wang and Sheeley (1990, 1991) did not prove to be effective enough. Even when the entire array of data was split into subranges, the application of this parameter provides a correlation coefficient of only about 0.4. It is interesting, that for the *Ulysses* spacecraft data, the application of this parameter gave somewhat higher correlations (up to 0.7) at high latitudes, but in the ecliptic plane the correlation was still low (Wang *et al.*, 1997). The parameter δ, suggested by Zhao and Hundhausen (1981) and Hakamada and Akasofy (1981), which is equal to the angular distance from the Earth's helioprojection to the heliospheric current sheet, was also ineffective.

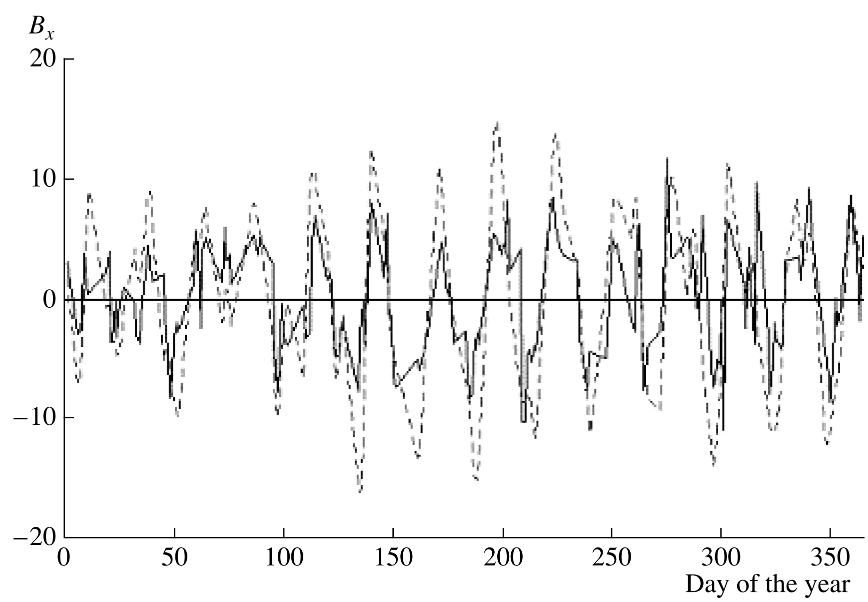

Fig. 5. Measured (solid curve) and calculated (dashed curve) time behavior of B_x in 1991.

Earlier we already concluded that the relationship between the solar magnetic fields and the solar wind depends on many factors and solar–terrestrial parameters. An additional complexity of the problem is that these parameters are not independent, and thus a common scheme based on the subsequent use of univariate regressions has no prospects in this case. Therefore, we preferred the least-squares method with two initial parameters.

The divergence parameter f_0 was chosen as the first parameter because its application is based on weighty enough physical arguments connected with models of coronal holes. However, we confined ourselves to the points at which $f_0 < 0.25$. Higher values are nonphysical and probably statistically unreliable. This parameter characterizes the magnetic field structure near the Earth's helioprojection point. It was natural to take the value characterizing the strength of large-scale fields for the second parameter. We chose $|B_{ss}|$ and rejected the points where $|B_{ss}|$ was higher than the double annual mean. This rejection was made in order to remove values with strong contribution of local fields.

$$V = 1000\alpha_f f_0 + 100\alpha_{ss}|B_{ss}| + 100V_0. \qquad (7)$$

The correlation of the solar wind speed V with the divergence parameter f_0 and the field on the source surface at the Earth's helioprojection point $|B_{ss}|$ is shown in Fig. 6. Thin solid lines and dashed lines demonstrate univariate correlations with f_0 and $|B_{ss}|$, respectively; the thick line shows the results of computations by formula (7). It can be seen that a bivariate regression somewhat increases the correlation everywhere; the effects of both parameters supplement each other. The application of $|B_{ph}|$ as the second independent parameter instead of $|B_{ss}|$ negligibly changes the results.

As the calculation of weakly disturbed solar wind was a part of our task and the calculation is based on parameters of quasi-stationary large-scale magnetic fields, it is not surprising that the highest correlations are achieved near the epochs of minimum of the 11-year cycle (1977, 1984, 1994). The correlation falls significantly near the cycle maxima; this probably results from an increased number of nonstationary processes and, firstly, coronal mass ejections.

We cannot say that the computation problem is solved completely till the parameters determining the coefficients in formula (7) are calculated. To find these links we used all available annual mean parameters of solar activity. They proved to be closely connected with those characteristics that determined the parameters in formulas (3)–(6). It is interesting that a direct comparison of parameters a_f, a_{ss}, and V_0 with parameters α found before (we do not present calculations here) gave coefficients of correlation that are considerably lower than those indicated in formulas (8)–(10). The dependence of a_f, a_{ss}, and V_0 on the tilting angle of the heliospheric current sheet and the Wolf numbers are shown

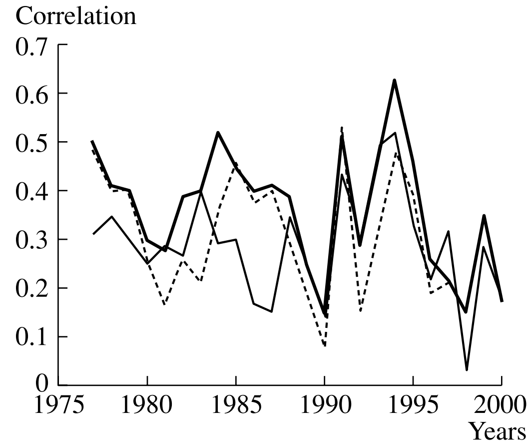

Fig. 6. The correlation of the solar wind speed V with the divergence parameter f_0 and with the field on the source surface at the Earth's helioprojection point $|B_{ss}|$. Solid and dashed thin lines show the univariate correlations with f_0 and $|B_{ss}|$, respectively; the thick line shows the results of computation by formula (7).

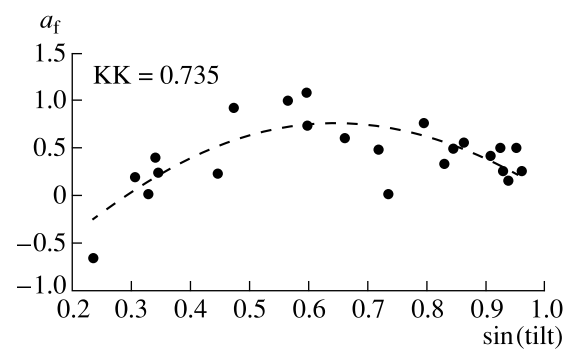

Fig. 7. The relation of the coefficient a_f to the tilting angle of the heliospheric current sheet.

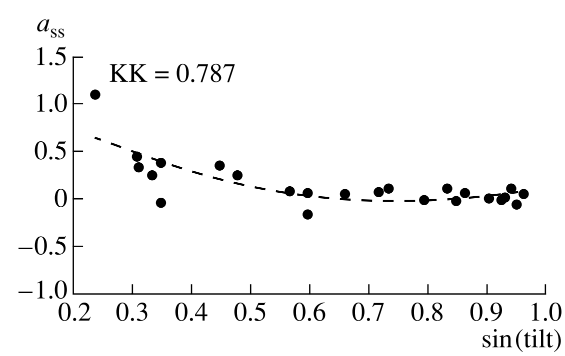

Fig. 8. The relation of the coefficient a_{ss} to the tilting angle of the heliospheric current sheet.

in formulas (8)–(10) and in Figs. 7–9. The second-order dependencies better reflect the decrease of a_f and a_{ss} with increasing tilting angle of the heliospheric current sheet. In total, the correlations for the speed are lower

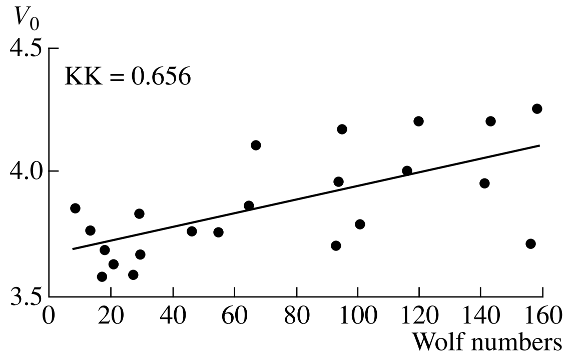

Fig. 9. The relationship between the coefficient V_0 and the Wolf numbers.

than those obtained during calculations of interplanetary magnetic field components.

$$a_f = -1.709 + 7.572\sin(\text{tilt}) - 5.808\sin^2(\text{tilt}), \quad \rho = 0.735, \tag{8}$$

$$a_{ss} = 1.379 - 3.702\sin(\text{tilt}) + 2.46\sin^2(\text{tilt}), \quad \rho = 0.787, \tag{9}$$

$$V_0 = 3.67 + 0.00275W, \quad \rho = 0.656. \tag{10}$$

THE MAGNETIC FIELD ENERGY IN A POTENTIAL REGION AND THE SOLAR WIND PARAMETERS

The application of the potential approximation model with a source surface results in energy characteristics in the heliosphere different from those obtained by the model without the source surface. Thus, it is of interest to calculate the magnetic field energy in a spherical layer between the photosphere and the level $R = R_S$. We can assume that the field is strictly radial (zero potential) at this level, that is we can use the model with the source surface. Such a field we shall call a bound field and shall denote by W_b its energy in the layer extending from the photosphere to R_S. If there is no source surface, the field freely falls as it is in vacuum, and the level R_S simply denotes the boundary of integration. Such a field we shall name a free field and denote its energy in the aforementioned layer by W_f. The formulas of calculating these energies were given by Ermakov (1995). It was demonstrated that the energy of a bound field is always smaller than the energy of a free field. This allows us to assume that part of the energy of the bound field is taken away to the heliosphere by the solar wind. In our previous work (Shelting, Obridko, 1996) we compared the differences of these energies $dW = W_f - W_b$, averaged over the Carrington revolutions and then smoothed for 24 revolutions, with the velocity V. The coefficient of correlation between these two values turned out to be rather high, but with a considerable and physically unclear shift of about several years. In the present section we shall compare the values of dW, W_f, and W_b, averaged over one revolution and not subjected to any smoothing or shifting, with heliospheric parameters.

We face a problem in understanding how the energy of the magnetic field is distributed between heliospheric parameters and what these parameters (dW, W_f, or W_b) are linked with most closely. The quantitative distribution of solar energy in different solar wind parameters was discussed in a number of papers. The indices determine the contribution of each component. For example, using the most simplified version, Akasofy and Perreault (Akasofy, 1978, 1981; Perreault and Akasofy, 1978) obtained that the energy transferred from the Sun by the solar wind is distributed in the magnetosphere between the solar wind itself and the magnetic fields proportionally to the product VB^2. Examining the *Ap* index, Ahluwalia (2000) came to the conclusion that the temporal variations of *Ap* are much better described by a function proportional to V^2B than by a function proportional to VB. He holds that the second formula describes the interplanetary electric field and helps to find the links between the magnetosphere and the solar wind. Kane (2002) arrived at the conclusion that the *aa* index shows a good correlation with two combinations of the solar wind speed and the interplanetary field—VB and V^2B. Belov *et al.* (2001) consider that it is more correct to use the product VB than simply the solar wind speed V when variations of cosmic rays are studied.

Note that the aforementioned papers discuss the combination of heliospheric parameters which affects the magnetosphere or cosmic rays most efficiently. On the contrary, we are looking for a combination of parameters, to which the energy of the solar magnetic field is transferred. Clearly, it is quite another problem. However, it is logical to try this link in the same functional form. We shall try a multicative–power form $\varepsilon = aV^mB^n$ for this link. Here ε stands for dW, W_f, or W_b, V is the solar wind speed, B is the modulus of strength of the interplanetary magnetic field near the Earth. All data are averaged over the Carrington revolutions. Obviously, the parameter a depends on normalization and the system of units applied and has no particular physical meaning.

Let us use a two-parameter model in the form of the logarithmic function

$$\ln\varepsilon = m\ln V + n\ln B + \ln a. \tag{11}$$

The analysis performed for 1976–2000 demonstrated that, if ε means dW, $m = 0.95$, $n = 1.12$ and the coefficient of correlation between the values of ε calculated from (11) and obtained directly from the solar data is equal to 0.33. These values are close to those given in the above-cited papers. But we must note that, when we analyzed not the entire data array but parts of it split into narrow intervals, the parameters m and n turned out to be highly variable. They vary strongly in

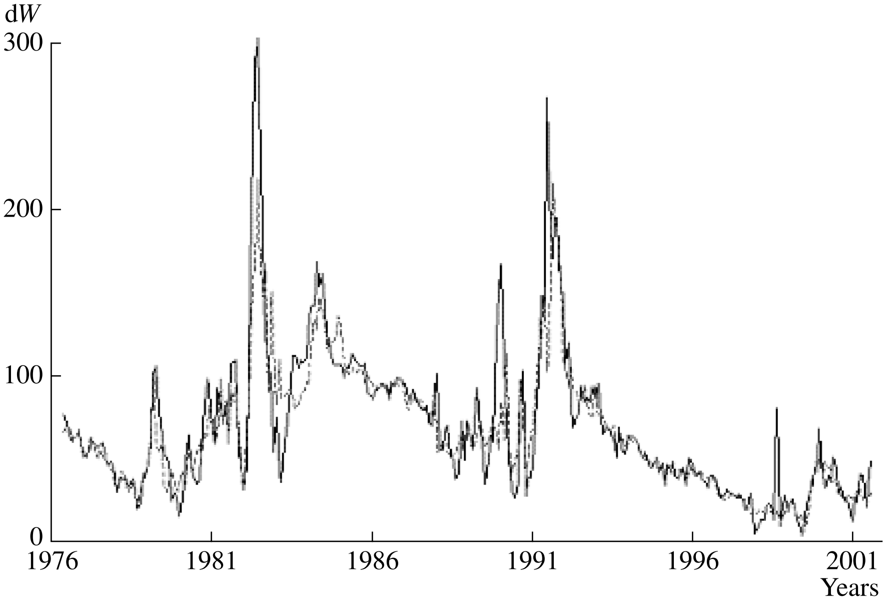

Fig. 10. The comparison of the values of dW calculated by formula (11) (dashed curve) and obtained directly from the solar data (solid curve).

value, and the parameter m even changes its sign at the cycle maxima. This is evidently associated with an increase of energy parameters combined with some decrease of the mean velocity at the maximum of cycles. However, this allows fitting for short intervals, and, then, we managed to obtain from formula (11) values of ε that are in good agreement with the initial ones. The results of one of such computations, in which the entire time interval from 1976 to 2000 (340 Carrington revolutions) was split into 13-CR intervals, are shown in Fig. 10 (the correlation coefficient is 0.84).

If we take W_f or W_b for ε (these cases differ little because W_f and W_b are close to each other), $m = -1.61$ and $n = 2.04$. This dependence does not resemble any of those cited above, but it reflects a very abrupt increase of energy indices at the cycle maximum accompanied by some decrease of speed. Note that the correlation coefficient is somewhat higher in this case and equals 0.46.

Higher correlation coefficients can be achieved if the parameters m and n are fitted for shorter intervals; however, we could not find any statistical regularity in the time dependence of m and n, which strongly vary in this case.

CONCLUSIONS AND DISCUSSION

We did not undertake the task of developing new methods of forecasting in our study. It is obviously impossible to make forecasts of solar wind characteristics by such a simple model like ours without taking into account a lot of other data, including the information on coronal holes, solar flares, and coronal mass ejections. All this information is applied in a real forecast, which is made with the use of data from many satellites and surface-based observatories for lead times of up to 1.5 days. Our task was to analyze correlations between some characteristics of the quiet solar wind and parameters of the large-scale magnetic field. A comparison of daily mean values of the interplanetary magnetic field (not only signs) with such correlation coefficients in such a simple model like ours (without complex double source surfaces or with rejection of the potentiality assumption) has not been performed so far.

The analysis performed confirms the possibility of calculating daily mean heliospheric parameters. This can be done most reliably for the magnetic field components B_x and B_y and a little worse for V.

It is important to note that these correlations are principally multi-parameter. In addition, we found that a nonlinear dependence on solar parameters should be taken into account in calculations. Therefore, frequently used additive methods can give useless results because both initial and calculated parameters occur in formulas in nonlinear fashion and are not independent.

The nonlinearity of the mutual correlations of heliospheric parameters was marked many times (for example, see a study of Shister and Shabanskii (1973)). In contrast, our note meant that it is the linear traditional link between the field on the source surface and the field in the heliosphere (when the field near the Earth is related to the field on the source surface with the use of a constant multiplier) that is not reliable.

The physical sense of the parameter α, introduced when the links with the interplanetary magnetic field components were analyzed, is not quite clear. For the present, we consider this parameter simply as an approximate one. However, it is worth noting that in theoretical formulas for the steady-state solar wind the

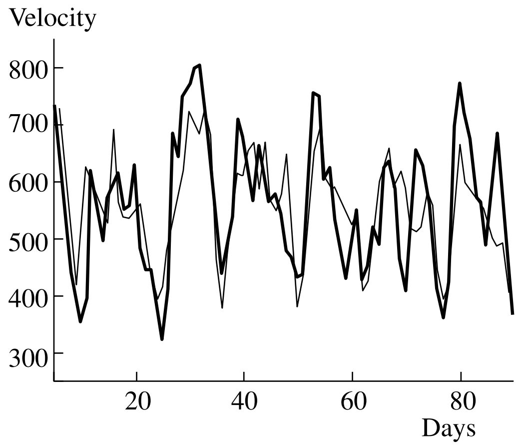

Fig. 11. The computation results for the three-parameter model for three revolutions. The first point corresponds to July 5, 2003. The velocities measured by the *ACE* satellite are shown by the thick line; the calculated values are shown by the thin line.

components, B_x and B_y must decrease as r^{-2} and r^{-1}, respectively (Parker, 1965; Toptygin, 1983). In our case, α_x and α_y nearly coincide and are from –1.4 to –1.7. This is probably connected with the fact that in the approximation we indirectly allowed for the transition to the solar wind along the acceleration curve. It is significant that, as one could expect, the absolute values of α_x and α_y increase with increasing tilt of the heliospheric current sheet. To some extent this result is methodologically close to the concept of Wibberenz *et al.* (2002), in which the coefficient of cosmic ray diffusion in the heliosphere is determined by the value B^{-n}, where n is between 1 and 2 and is determined by the tilt of the heliospheric current sheet. With an increase of the tilt at the maximum of solar activity, n grows and verges to 2; it falls to the values close to 1 at the minimum.

As we demonstrated earlier (Shelting and Obridko, 1996; Obridko *et al.*, 1996), when calculated and measured daily mean values are carefully compared, it turns out that, if the inverse quadratic dependence is used, the calculated values are less than the measured ones by a factor of 2–10. In this case, the factor of underestimation varies in a regular way; it is large at the maximum of the 11-year cycle and relatively small at the minimum. If we stay within the framework of the model with one source surface, this can be associated with the underestimation of the field on the source surface. This is most probably the manifestation of the weakness of the model, which assumes a sharp transition from the potential field area to the solar wind. The actual zone of transition must be extended and change depending on the global structure of the large-scale field, which varies with the cycle phase. The total effect of the divergence of field lines on the initial branch of the trajectory is simulated by the parameters that we introduced.

Of course, there is nothing surprising in the coincidence of the values of α_x and α_y. However, to make the experiment pure, we found them separately, especially as the ratio of B_x to B_y is constant only on average, and, in fact, changes strongly from day to day. On the other hand, the multipliers that we introduced are purely approximate ones and can be used only at a distance of one astronomical unit.

The calculation of the solar wind velocity is much less reliable. It is probably connected with the fact that the velocity (though it varies only slightly) depends more strongly on nonmagnetic parameters (in particular, on the local temperature of the corona), which are unknown. However, maybe we simply did not succeed in selecting the computation parameters that are significant for this problem. Nevertheless, it should be noted that the two-dimensional computation scheme used in our study improved the correlation between the measured and calculated values as compared to the one-dimensional scheme. Wang and Sheeley (1991) used only the divergence factor in their study and calculated only the probability that the velocity falls into one of four rather wide subranges. Then they calculated monthly mean values and applied a three-month smoothing. Only after this, did the authors obtained the correlation coefficient of about 0.5 ± 0.0. We (Obridko *et al.*, 1995, 1996) demonstrated that (1) this scheme is inefficient if daily values are used without any smoothing and that (2) it is necessary to introduce an additional energy index indicating the strength of the magnetic field in the area of wind outflow. This scheme was implemented in the present study. The correlation coefficients attained in this case are certainly not high, but they are the largest of those obtained before for unsmoothed daily mean velocities in one-dimensional computation schemes.

To make it clearer, we subjected the computations made by our model to averaging and smoothing similar to those used by Wang and Sheeley. We obtained the correlation coefficients equal to 0.84 ± 0.05 in 1979–1981 and 0.90 ± 0.03 in 1993–1995. These values are certainly higher than those in the cited paper of Wang and Sheeley (0.57 ± 0.19). Thus, the computations by the model which takes into account not only the divergence but also the strength of the magnetic field, are in better agreement with observations than those calculated by the cited model of Wang and Sheeley, where only the divergence was allowed for.

Note that the model for the solar wind speed, which is described by formulas (7)–(10), allows one to understand the basic physical links for the quiet solar wind and indicates that not only divergence but also the strength of the magnetic field should be taken into account. But this model cannot be applied in practical forecasting because of insufficiently high coefficients of correlation in formulas (8)–(10). This is associated with the fact that the coupling coefficients a_f, a_{ss}, and V_0 are unstable and can vary rapidly. The application of annual mean values for these coefficients, in this case, does not give reliable results. That is why the computation scheme based on current observations, in which the coupling coefficients a_f, a_{ss}, and V_0 are recalculated every time using a relatively short (1–3 revolutions) training sequence directly before the forecast date, has more prospects. Apparently, it is this scheme that is realized in the last model of Wang and Sheeley; the results of which are given at the site http://www.sec.noaa.gov/ws. However, no information on the forecast skill is given at the site. Similar calculations were also made at the Institute of Solar-Terrestrial Physics in Irkutsk.

The computational results obtained by our three-parameter model (7) for three revolutions are given in Fig. 11. The first point corresponds to July 5, 2003. The velocities measured by the *ACE* (Advanced Composition Explorer) satellite are shown by the thick line and the calculated values are shown by the thin line. The correlation coefficient is 0.71 ± 0.054.

We intend to discuss in more detail the application of the computation method based on current observations and the three-parameter scheme in another publication.

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