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Solar Wind Variation with the Cycle

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Abstract. The cyclic evolution of the heliospheric plasma parameters is related to the time-dependent boundary conditions in the solar corona. "Minimal" coronal configurations correspond to the regular appearance of the tenuous, but hot and fast plasma streams from the large polar coronal holes. The denser, but cooler and slower solar wind is adjacent to coronal streamers. Irregular dynamic manifestations are present in the corona and the solar wind everywhere and always. They follow the solar activity cycle rather well. Because of this, the direct and indirect solar wind measurements demonstrate clear variations in space and time according to the minimal, intermediate and maximal conditions of the cycles. The average solar wind density, velocity and temperature measured at the Earth's orbit show specific decadal variations and trends, which are of the order of the first tens per cent during the last three solar cycles. Statistical, spectral and correlation characteristics of the solar wind are reviewed with the emphasis on the cycles.

Key words. Solar wind—solar activity cycle.

1. Introduction

The knowledge of the solar cycle variations in the heliospheric plasma and magnetic fields was initially based on the indirect indications gained from the observations of the Sun, comets, cosmic rays, geomagnetic perturbations, interplanetary scintillations and some other ground-based methods. Numerous direct and remote-sensing spacecraft measurements *in situ* have continuously broadened this knowledge during the past 40 years, which can be seen from the original and review papers. We do not intend here to present the complete list of publications on this very popular topic and restrict ourselves by the selected set of references chosen more or less arbitrary for the introductory purposes only (Feldman *et al.* 1977; Crooker 1983; Veselovsky 1984; Schwenn 1990; Hapgood *et al.* 1991; King 1991; Gazis 1996; Richardson *et al.* 1996; El-Borie *et al.* 1997). See also related papers presented by S. Ananthakrishnan and P. Kiraly at the Kodaikanal meeting.

Interplanetary scintillation measurements demonstrated the existence of the heliolatitudinal solar wind velocity dependence on the solar cycle (Vlasov 1975, 1983, 1998; Coles *et al.* 1980; Bourgois & Coles 1989; Kojima *et al.* 1990; Lotova & Korelov 1991; Ricket & Coles 1991; Manoharan 1993; Coles *et al.* 1995). Ulysses measurements *in situ* confirmed and detailed these results regarding the solar minimum period. The solar cycle change in the solar wind dynamic pressure occurs at all solar latitudes, in both the fast and slow solar wind (Richardson *et al.* 1999).

The aim of this paper is to present a short review of recent studies of the solar wind variation with the cycles. More details and some working materials of the ongoing study can be found at the Web site (http://alpha.npi.msu.su/alla).

2. Average parameters

Solar cycle variations of all heliospheric plasma and magnetic field parameters of an order of ten per cent are well documented (Veselovsky *et al.* 1998, 1999, 2000a, 2000b; Dmitriev *et al.* 2000). As an illustration, Fig. 1 shows the monthly averaged values of the main solar wind parameters. The curves are noisy, but some regular solar cycle changes can be recognized and they are confirmed by the detailed analysis. The solar cycle variations appear more clearly when longer time averages are invest-tigated. We performed this analysis with different kind of running averages, for example, over three, six and twelve months with the following results. The maximal densities are observed at the rising and declining solar cycle phases. The maximal velocities and temperatures appear at the declining phases, when the hotter and faster solar wind streams from large polar coronal holes reach the ecliptic plane. Heliospheric and solar magnetic fields are well correlated and follow the activity cycle.

Solar cycles are clearly seen in the energy, momentum and mass fluxes of the solar wind. The Sun as a star emits by a factor of 1.5–2 more solar wind mass and energy during solar minima in comparison with solar maxima years. Moreover, the overall rising trend of the same order of magnitude during the past 30 years can be marked (see Fig. 2).

3. Statistical and spectral-time analysis

Not only average values, but also statistical properties of the solar wind parameters are solar cycle dependent. The physical reason for these lie in the solar activity regulation of the corona and wind sources.

The statistical distributions of the solar wind parameters are varying during solar cycle while remaining close to the log-normal laws with remarkable deviations. The information entropy is rather high, but different types of the solar wind flows are discernible. For example, fast solar wind “islands” are clearly seen in Fig. 3 for the velocity distributions during the declining phases (1974, 1985, 1994). More details can be found in the paper (Veselovsky *et al.* 2000b).

Multi-parametric cross-correlation analysis indicates that the best correlations between different solar wind parameters are observed under the averaging time of about one year. For the averaging times greater and less than this value one obtains a lower degree of correlation. The tentative explanation of this fact could be related to a relatively high level of fluctuations associated with the solar activity and the solar rotation, which is demonstrated in the next section.

Extremely high correlations were marked between the heliospheric magnetic field, the magnetic field of the Sun as a star and galactic cosmic ray variations (Belov *et al.* 1999). This allowed reconstructing heliospheric magnetic fields for the past times

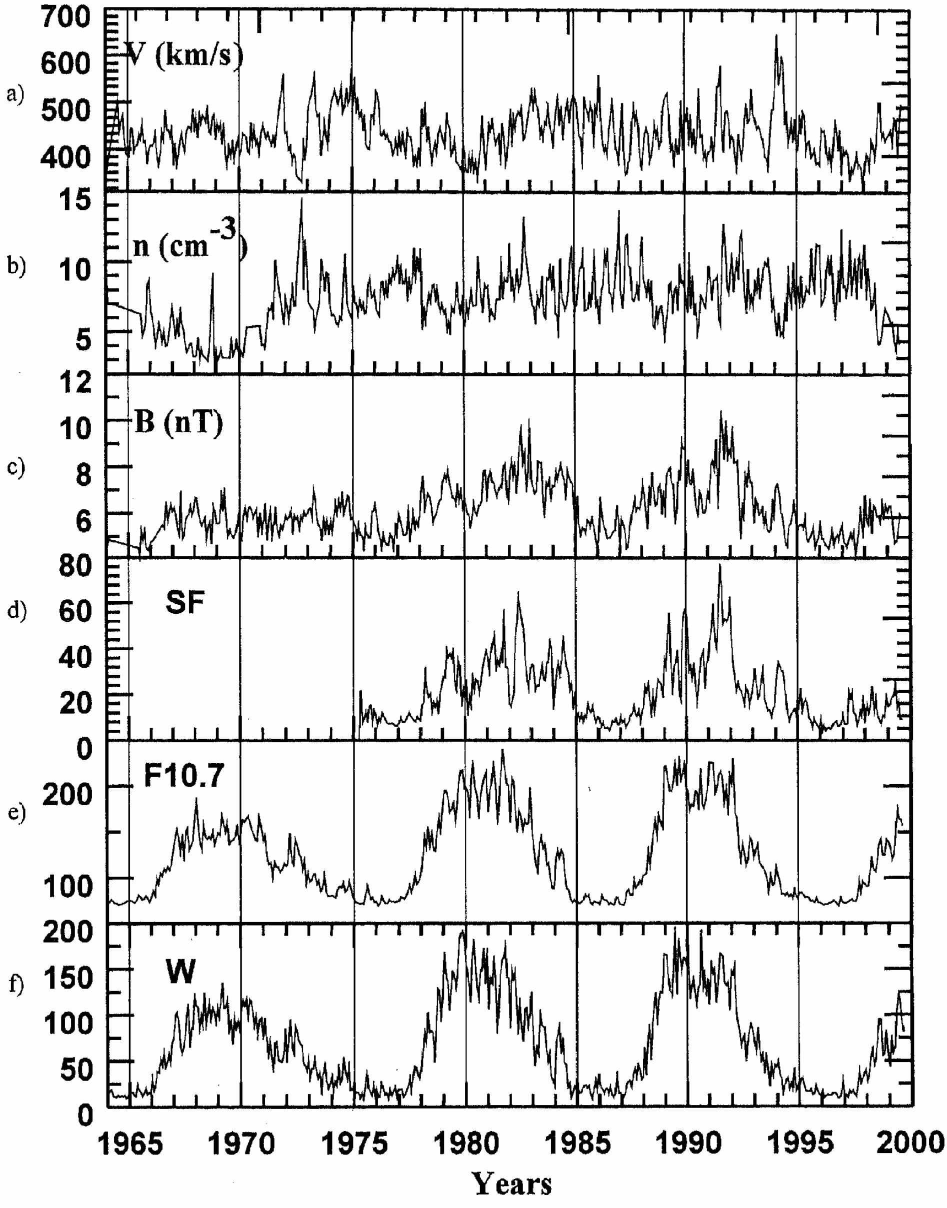

Figure 1. Monthly averaged values of the main solar wind parameters at the Earth's orbit and solar indexes: (**a**) solar wind velocity V (km/s); (**b**) solar wind number density n (cm^{-3}); (**c**) helisopheric magnetic field B (nT); (**d**) magnetic field of the Sun as a star SF; (**e**) solar radioemission index F10.7; (**f**) sunspot numbers W.

using neutron monitor data. Osherovich *et al.* (1999) described a strong correlation between the inverse square Alfven-Mach number M_A yearly medians and sunspot numbers.

Fast Fourier-transforms, spectral-time and wavelet analyses were applied for the investigation of the rythmic and non-rythmic long-term variations during the solar

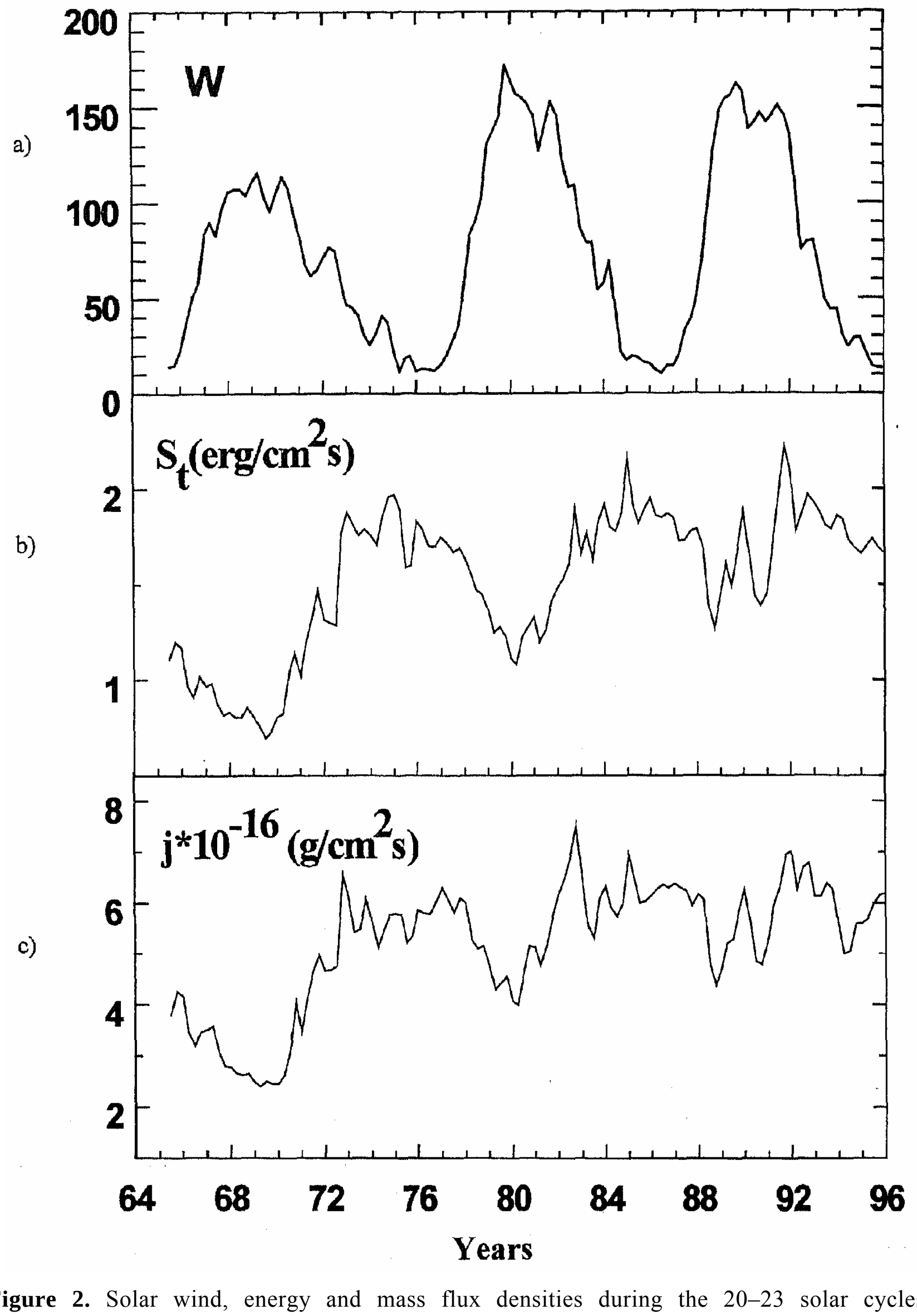

Figure 2. Solar wind, energy and mass flux densities during the 20–23 solar cycles. (**a**) sunspot numbers; (**b**) solar wind energy flux density S_t;(**c**) solar wind mass flux density *j*

cycles with time scales from days to tens of years. The results of this investigation (Veselovsky *et al.* 2000b) show a large manifold of the regular and irregular solar wind variations at the Earth's orbit which are explained by the following causes: 1) the solar variability; 2) the solar rotation with inhomogeneities in the corona; 3) the Earth's orbital motion.

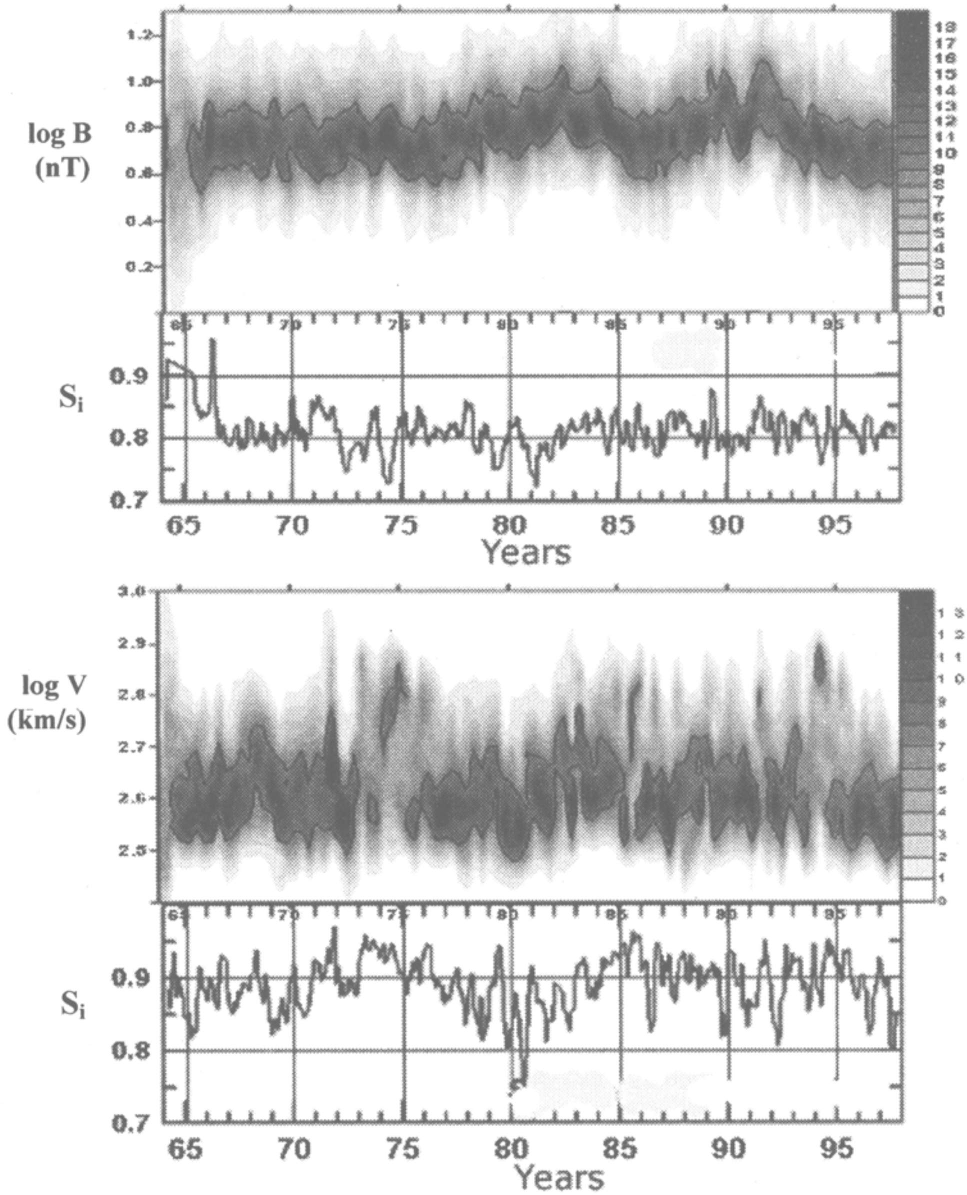

Figure 3. Statistical distributions and the information entropy of the hellisopheric magnetic field (upper panels) and the solar wind velocity (bottom panels). The color scale (right) was partially lost because of the white-black reproduction of the running histograms. Nevertheless, the level contours can be followed. In particular, the solid line is shown at the half-height of the histograms.

4. Discussion

It is well known that the large-scale 3-D organization of the solar corona and the heliosphere is regulated by the solar activity. Fast, tenuous and hot (slow, dense and cold) quasistationary solar wind flows usually correspond to the open (closed) magnetic configurations on the Sun represented by coronal holes (active regions). Coronal holes (active regions) are well developed around the solar minimum (maximum) years. The non-stationary transient flows, coronal mass ejections, or corpuscular streams according to the old terminology, correspond to more complicated and dynamical magnetic configurations on the Sun, both open and closed, as well as intermittent in space and time (Veselovsky 2000).

The demarcation between the non-stationary ($S \ll 1$) and quasistationary ($S \gg 1$) cases is given by the Strouhal number $S = Vt/l$, where V, t and l are characteristic velocity, time and space scales. The marginal value $S \approx 1$ corresponds to the time scales of the order of days for the Earth's orbit. Detailed knowledge is needed of the governing laws and different regimes in the heliosphere for a better understanding of the possible predictability limits when using neural network models (Veselovsky *et al.* 2000a).

5. Conclusions

- Heliospheric plasma parameters show solar cycle variations and longer-term trends. Both regular and irregular components are present. The regular changes are distinct in many instances, but they are relatively small and sometimes obscured by large fluctuations.
- The magnitude of the solar wind variations during the past solar cycles (20–23) is of the order of several tens of per cent.
- The cyclic variability of the Sun as a star on the factor about 1.5-2 is clearly seen in the integral mass and energy losses with the solar wind outflow.
- The observed variations do not contradict the concepts of the solar wind origins from the magnetically open, closed and intermittent structures in the solar corona.

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