Solar wind and interplanetary magnetic field features before magnetic storm onset

O. Khabarova, V. Pilipenko, M.J. Engebretson, and E. Rudenchik

Abstract: The presented results, concerning the features of the solar wind plasma structure as observed by spacecraft upstream of Earth, could be used for development of middle-term forecasts of magnetic storms. We have analyzed 1-hour data for 1995-2005 and a whole year of 1-min data during solar minimum (1995) and during solar maximum (2000) with 48 and 60 storms, respectively. The long-term statistical correlations between the solar wind/IMF parameters are found to vary during the solar cycle, and this fact should be taken into account for the prognostic aims. During solar maximum the yearly correlation of V with ground geomagnetic indices drops, and the correlation of N with these indices becomes significant during solar minimum only. Elevated solar wind density enhances statistically the IMF magnitude, but not the IMF Bz component. A remarkably high correlation exists between the low-frequency solar wind plasma turbulence with time scales 4-32 min and the IMF magnitude. It was shown that solar wind dynamic pressure variations are mainly determined not by speed, but density. The density changes play a significant geoeffective role. In many cases magnetic storms with -30 nT$< Dst <$-100 nT are the result of sharp increases in solar wind density with consequent negative Bz at the background of low and steady solar wind velocity. Besides, about 2 days before ∼80% of magnetic storm commencements a weak increase of density is observed. This increase of the solar wind density is irregular and accompanied by fluctuations with time scales $\sim 2-120$ min, on the average, 2 days prior to storm commencements. The possible mechanisms of these pre-storm solar wind/IMF variations have not been firmly established yet. Thus, variations of the solar wind plasma are a largely underestimated factor in magnetic storm triggering and could be effectively used for space weather forecasting.

Key words: magnetic storms, solar wind, geomagnetic storm forecasting.

1. Introduction

Magnetic storm forecasting is one of the most important problems of solar-terrestrial physics and the keystone of space weather science. As in seismology, forecasting methods can be roughly classified into short-term (about 1 hour in advance using spacecraft measurements at the L1 point), middle-term (from several hours to several days), and long-term (solar cycles). The short-term forecasts are rather exact, up to $\sim 90\%$, but their alert time ($\Delta T < 1$h) is too small for usage of this information in practical aims. The quality of medium-term forecasting remains rather modest: during solar maximum the successful forecasting rate is ∼75% (see, for example, the Lund Space Weather Center and Naval Research Laboratory webpages). However, the actual forecast quality is lower, because most of the medium-term forecasting methods are oriented toward the prediction of probability of severe storms only, and, drops to ∼30% during solar minimum [1]. There are several unsolved problems, leading to our inability to produce the desired level of middle-term prognosis of geomagnetic storms.

Direct monitoring of solar eruptive processes cannot solve the problem of middle-term magnetic storm forecasting, because it is very uncertain whether an ejecta would reach the Earth and how a solar plasma stream would evolve upon the propagation.

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One of the main reasons is that most of the techniques used for magnetic storm forecasting are oriented toward the prediction of severe magnetic storms, with $Dst < -100$ nT. It is commonly assumed that the majority of severe magnetic storms ($\sim 80\%$) are caused by the arrival of magnetic clouds (MCs) from coronal mass ejections (CMEs) and, to a much lesser extent, by corotating interaction regions (CIRs) [2, 3]. As a result, the space weather community is overwhelmingly oriented to the study of CMEs with a strong southward interplanetary magnetic field (IMF), so the following paradigm has been formed: ”The main controlling factors of geomagnetic activity are the solar wind speed V and the north-south IMF component Bz”.

However, the number of strong storms is less than 10% of the total storm number [2]. Meanwhile, less intense storms should not be disregarded because of their seemingly low geoeffectiveness. There are many examples indicating that moderate storms ($Dst \sim -50$nT) often produce much higher increases of relativistic electron fluxes near the geosynchronous orbit than intense storms ($Dst < -100$ nT) do [4, 5].

Most of the medium-term forecasting methods are oriented towards the prediction of the probability of CME arrival. Meanwhile, according to recent investigations, the existing estimates of the geoeffectiveness of real CMEs are close to estimates of the geoeffectiveness of solar flares (30-40%) [6]. At the same time, for a random distribution of solar processes and magnetic storms the formally calculated coefficient of correlation can be 30-40%. This value is comparable with the forecast success rate ∼30% during the solar minimum [1].

Commonly, the geoeffectiveness of the solar wind is overwhelmingly characterized by the combinations of the velocity V and the IMF Bz component: the interplanetary dawn-dusk electric field $E_{EW} = V * Bz$ or total electric field $E_T = V * B$. Implicitly, the paradigm of determining the role of CMEs and E_{EW} has been expanded to all the processes of solar wind-magnetosphere interaction. Sometimes, e.g. [2], a magnetic storm is even defined as ”an interval of time when a sufficiently intense and long-lasting interplanetary convection electric field leads ... to an intensified ring current strong enough to exceed some key threshold of the quantifying storm time Dst index”. This definition assumes that all other factors of the solar wind and IMF play no role in the storm production, and the only physical mechanism influencing the magnetosphere is reconnection. Such solar wind/IMF parameters like plasma density N, level of turbulence, etc., commonly have not been taken into account and examined for their geoeffectiveness. In particular, density was considered as a minor factor, just increasing the storm intensity or enhancing negative Bz at the leading edge of a magnetic cloud [7].

Meanwhile, statistical analysis shows that upon a decrease of magnetic storm intensity, the solar wind velocity has ever diminishing influence on Dst disturbance. Only 23% of mild storms with -50nT$< Dst <$-30nT are related to high-velocity streams [2]. At the same time, there are indications of the geoeffectiveness of other solar wind/IMF parameters, especially the solar wind plasma density which might enhance the effect of southward IMF and production of the ring current [8, 9]. Introduction into a forecasting algorithm of solar wind dynamic pressure improved the quality of short-term storm prediction, especially for the most intense storms [10].

It would be an intriguing possibility to find an alternative approach to medium-term forecasting, in which solar wind/IMF features might be used as a prognostic factor. It is worthwhile to pay more attention to the solar wind plasma density, a still underestimated factor of storm stimulation as compared with the recognized storm-makers - velocity and IMF Bz [11]. This paper is mostly focused on the study of features of the solar wind and IMF dynamics before magnetic storm onset, with special emphasis on solar wind density and its fluctuations.

2. Data, techniques, and features of magnetic storms under study

To characterize the solar wind changes and magnetospheric disturbances we have used speed V, proton concentration (density) N; and IMF from Wind and ACE spacecraft, as well as SYM-H and Dst indices. We have analyzed statistically the interval 1995-2005 on the basis of hourly OMNI data and have tested in detail an entire year of 1-min Wind spacecraft data during solar minimum (1995) and solar maximum (2000).

To estimate the power of the solar wind density fluctuations we have used the database of hourly ULF indices [5] - the spectral power of IMF and N fluctuations integrated over the 2-7 mHz frequency band. Additionally, we have applied the wavelet technique to estimate the integrated power W_N of density fluctuations with various time scales (commonly, from 4 to 32-64-128 min) with 1-min cadence.

In order to have the possibility to analyze statistically prestorm intervals we must know how to identify magnetic storm onsets. For automatic detection of storm onset we have applied the following algorithm. We have calculated a 30-minute moving gradient of the SYM-H index, $\nabla_{30min}|\text{SYM-H}|$, where the gradient has been estimated as the tangent of the inclination of the autoregression straight line for 30 points. A storm onset was reported when the absolute value of this gradient had exceeded a certain threshold value (0.3) before geomagnetic indices (Kp, Dst) indicated disturbed conditions at least 2 hours after this moment. This algorithm reliably detected an SSC moment as well as an onset of magnetic storm growth phase without SSC. In contrast to the technique proposed here, the usage of hourly Dst and 3-hour Kp indices enables one to detect the storm main phase onset, but not the onset of the growth phase. With application of this technique, 48 and 60 storms with $Dst < -30$ nT were detected during 1995 and 2000, respectively.

A histogram of magnetic storm occurrence with respect to its intensity is shown in Fig.1 for two phases of solar activity cycle: minimum, 1995-1996, and maximum, 2000-2001. According to the IAGA SSC catalogue, all the storm events have been classified as storms with SSC (dark columns) and without it (gray columns). The distribution of intensity of magnetic storms with identified origins (whenever it was possible) is also shown in Fig.1: CIR-related storms (marked by diagonal lines), and MC-related storms (white columns). During both the solar minimum and maximum years, the geoeffectiveness of CIRs and MCs in the production of medium and severe magnetic storms was nearly equal, which is in a good correspondence with [6], but in contrast to the commonly accepted point of view about the prevailing geoeffectiveness of MCs. The number of storms caused by CIRs is about 1.7 times larger than the number of storms caused by MCs both during solar minimum and maximum. Overall storm statistics show that such events as CIRs and MCs are rather rare, so most storms are produced either by recurrent streams without evident CIR, or

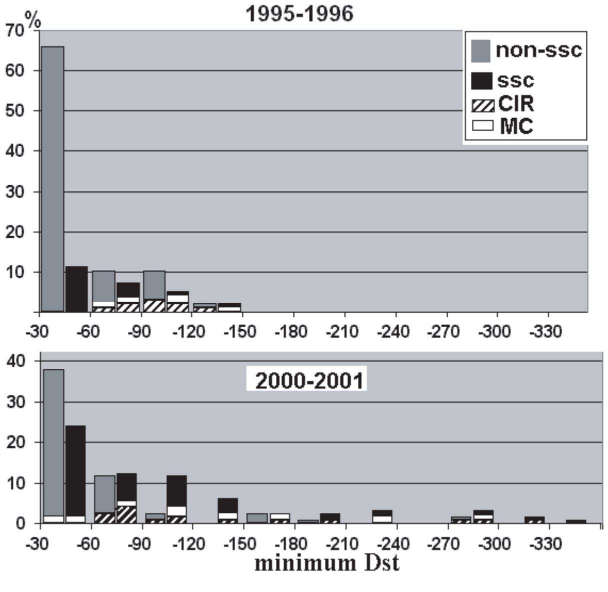

Fig. 1. Histograms of magnetic storm occurrence (in %) in respect to their intensity (as measured by the Dst index) for solar minimum (1995-96) and solar maximum (2000-01) for various categories of magnetic storms: with SSC (black), without SSC (gray), CIR-produced (diagonal lines), and MC-produced (white).

by streams of mixed origin [13]. Therefore, it would be useful for prognostic aims to classify the geoeffectiveness of the solar streams not by their affiliation with CIRs or MCs, but by simple physical characteristics: velocity, density, magnetic field, and the intensity of the magnetospheric disturbances produced.

3. Relationships between basic solar wind and geomagnetic activity parameters

For a long time it was supposed that the solar wind dynamic pressure $D = NV^2$ is the dominant geoeffective factor influencing storm development. Though since that time the paradigm in storm studies has changed, variations of the dynamic pressure are still one of the key space weather parameters, influencing, for example, the size and shape of the magnetosphere. Then, a question arises: which of the components - density or velocity - are most significant for pressure variations? Are the mechanisms of the magnetospheric response to the variations of N and V different or the same?

It might seem that velocity is geoeffective [14] because it provides a second power contribution ($\propto V^2$) to the dynamic pressure variations. However, analysis of solar wind data has shown that the possible geoeffectiveness of solar wind dynamic pressure is determined mainly by changes of density, but not velocity. The correlation coefficient between plasma density and dynamic pressure is $R \simeq 0.8$, which is about 10 times more than that between the speed and dynamic pressure (for 1-min cadence data for 1995 and 2000). Therefore, we examine in greater detail the statistical properties of the solar wind density, because variations of N may be significant for storm dynamics and space weather purposes.

For space weather forecasting purposes it is important to know whether the relationships between different interplanetary parameters and their geoeffectiveness are stable from year to year and independent of solar activity level. We have found that statistical relationships between the solar wind and IMF parameters have turned out to differ, sometimes significantly, at various solar cycle phases (Fig. 2). The following results of correlative analysis should be highlighted:

During solar maximum the correlation between V and Dst dropped to $R \simeq 0.3$ (Fig. 2a). The correlation between N and Dst is significant ($R \simeq 0.4 - 0.5$) during solar minimum only. Correlation between Bz and Dst is stable and statistically significant, but low, $R \simeq 0.2 - 0.4$ (Fig. 2b).

The correlation between N and Bz is practically absent (Fig. 2b). Thus, the popular hypothesis about an increase of southward IMF by an enhanced N [7] has not been supported by our statistical results. Meanwhile the correlation of N with IMF magnitude $|B|$ is much higher. Thus, the solar wind density indeed can drag and compress the IMF lines, but N equally enhances IMF of any direction, not only southward.

A remarkably high correlation between the low-frequency solar wind plasma turbulence, as characterized by the wavelet power W_N of density fluctuations with time scales 4-32 min and IMF magnitude $|B|$ is observed: $R \simeq 0.40 - 0.55$ (Fig. 2c). Thus, the high magnitudes of IMF are commonly accompanied by an elevated level of solar wind plasma turbulence. A surprisingly high correlation is observed between the wavelet power W_N and Kp (Fig. 2c). We also checked the geoeffectiveness of various solar wind / IMF parameters. The correlation between the most famous storm-makers, the interplanetary electric fields E_{EW} and E_T, and the Dst and Kp indices is shown in Fig. 2d. The highest and most stable correlation coefficient is observed between E_T and Kp, in good correspondence with [12]. Our analysis also shows, rather surprisingly, that $E_{EW} - Kp$ and $E_{EW} - Dst$ correlations are not so high (Fig. 2d), comparable with the $Bz - Dst$ correlation (Fig. 2a).

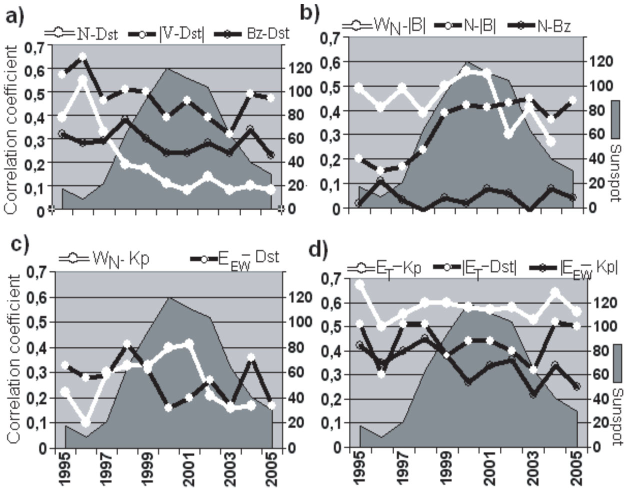

Fig. 2. The yearly variations of pair correlation coefficients between various solar wind/IMF parameters and geomagnetic indices for the solar cycle period 1995-2005.

These facts may indicate that intrinsic properties of the solar wind and IMF, as well as their magnetospheric response, vary during a solar cycle. Therefore, storm prediction algorithms must adapt to these variations, otherwise they would be not equally effective during various phases of solar cycle.

4. Magnetic storm driving by the solar wind density and IMF

There is a common view that magnetic storms are produced by extended intervals (more than $\sim$ 3 hours) of southward $Bz < 0$, whereas V determines the storm intensity, because the main driver is supposed to be the interplanetary electric field E_{EW}. However, this rule works for severe storms only, and in reality just a moderate southward IMF, even with high V, is not sufficient to produce a storm. For example, between 04/30 and 05/02, 1999 (Fig. 3a) there were many intervals with $Bz \simeq -2$ nT with duration of a few hours under high $V \simeq 600 - 650$ km/s and low N, but they have not produced any significant disturbance ($Dst > -30$ nT). At the same time, mild and moderate magnetic storms can be produced by moderately negative Bz without significant growth of V, but after substantial and steep N growth (see examples in Fig. 3b-d).

In total, 84 storms ($\sim$ 80%) with $Dst < -30$ nT, during both solar minimum (1995) and maximum (2000), were preceded by a rapid solar wind density increase, whereas the velocity growth occurred after storm development. The delay between a rapid rise in density and a velocity peak is commonly about 1 day, therefore a storm is in its recovery phase

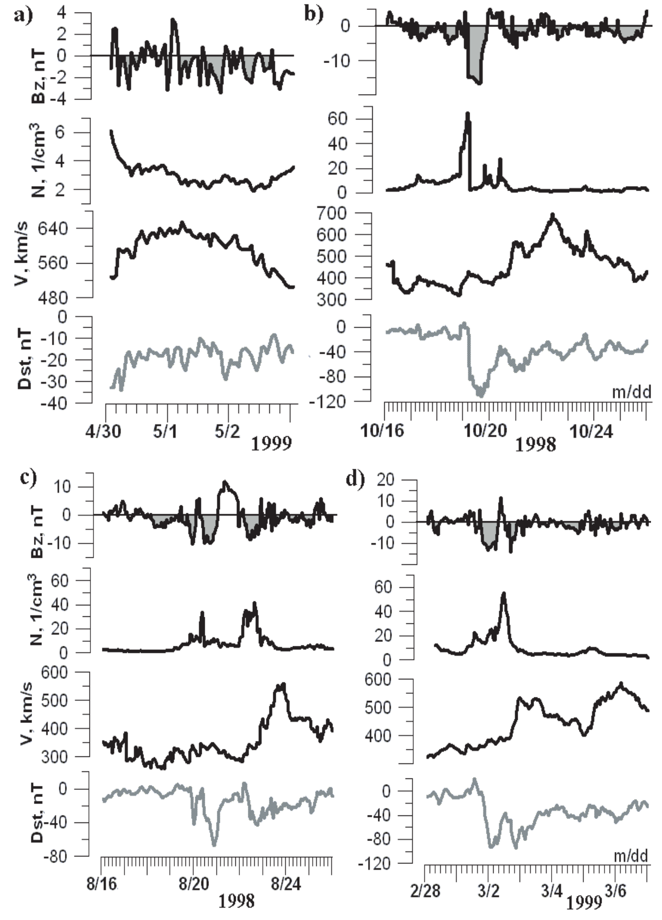

Fig. 3. Variations of the IMF Bz component, solar wind density N and velocity V (taken from OMNI), and the Dst index during space weather events on (a) 04/30-05/02, 1999; (b) 10/16-10/26, 1998; (c) 08/16-08/26, 1998; and (d) 02/28-03/07, 1999.

during the arrival of the high-speed-stream. So, the usually cited conditions of the storm production ”long-term occurrence of southward IMF and high velocity” are not both equally necessary. For example, Fig. 3c shows the event when two subsequent storms have been stimulated with some delays by rapid increases of N at the background of low V. However, in another event (Fig. 3d) the first storm is triggered by the N increase, whereas the second storm is related to the increase of V.

Probably, in events like these the loading-unloading mechanism supplies energy into the magnetosphere, maybe even during periods preceding storm onset. This energy is eventually released as a magnetic storm only after strong ”shaking” of the magnetosphere by the high pressure solar wind pulses.

5. Behavior of solar wind parameters prior storm onset

Case-study analysis shows that the solar wind behavior before a magnetic storm persistently demonstrates important features. Besides the rapid increase of the plasma density, provoking magnetic storm beginning, a more gradual increase of N occurs for a few hours or even days before the main density growth. The increase of N is not steady, but is accompanied by irregular fluctuations. These features can be used as a storm precursor.

Typical features of the solar wind before magnetic storm onset are illustrated by the 03/21-03/29, 1995 event (Fig. 4a). The increase of N is accompanied by an elevated level of density fluctuations with time scale 4-32 min, as revealed by the wavelet power, and strong changes in the 6-h running gradient of density. This case describes a typical situation, when a magnetic storm has precursors in the solar wind: a weak and irregular increase of density before the main jump of N. The observations of case studies such as the above are confirmed by the following statistical analysis. We have compared two distributions of various interplanetary parameters from 1-min Wind data: overall yearly distribution (white bars) and distribution during time intervals before magnetic storm onsets (dark bars). The comparison of these distributions has shown that:

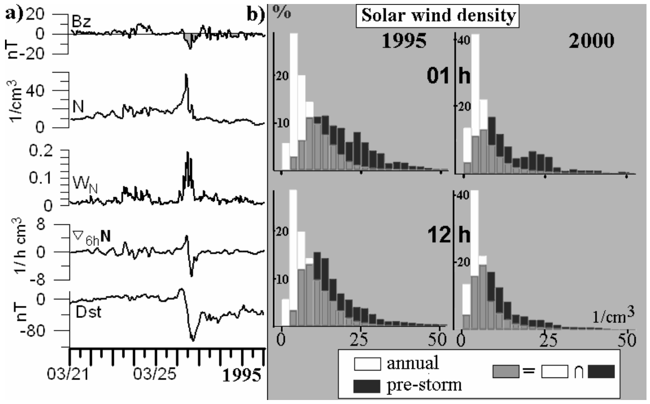

Fig. 4. (a) Variations of IMF Bz component, solar wind density N, wavelet power of density fluctuations W_N, six-hour running gradient of N, and the Dst index during the magnetic storm of 03/21-03/29, 1995. (b) Histograms of statistical distributions of N for the whole year and for the periods 1 hour and 12 hours before storm onsets for 1995 (left-hand panels) and 2000 (right-hand panels).

The pre-storm density values are increased in comparison with the annual distribution (Fig. 4b) both for the year of maximum (1995, left-hand panel) and minimum (2000, right-hand panel) of solar activity. This increase is observed at time intervals 1 hour (upper panels) and 12 hours (bottom panels) before storm onset. The effect becomes weaker for the time interval 24 hours and entirely disappears at the 2 day interval (not shown). The solar wind velocity, on the other hand, demonstrates a tendency to decrease slightly before storm onsets, both during solar minimum and maximum. Density fluctuations in the ULF range are enhanced before onset, as revealed by the shift of the distribution of the T_N index to higher values, both during solar minimum and maximum (Fig. 5). This enhancement becomes less evident for the 2 day interval. The tendency of increase of background solar wind density and its variability before magnetic storms can be seen from histograms of the distribution of running 6-hour gradients of N for the entire year and periods before storms (Fig. 6). Before storms the magnitude of the density gradient increases both during

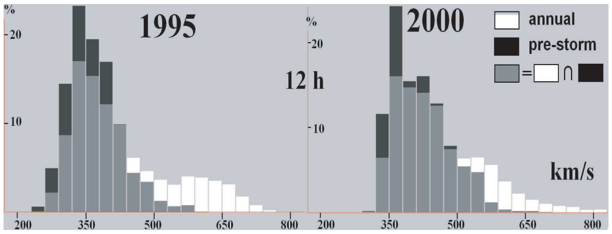

Fig. 5. Comparison of histograms of annual distributions and pre-storm distributions of the solar wind velocity during solar minimum (1995) and maximum (2000) for 12 hours time intervals before storm commencement.

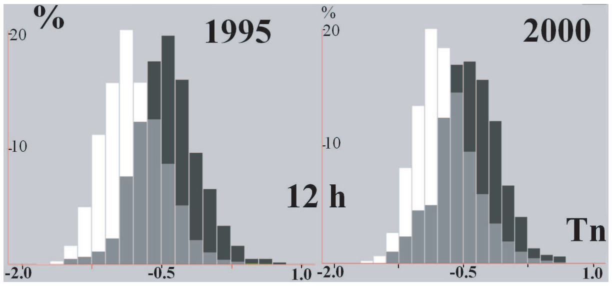

Fig. 6. Comparison of histograms of annual distributions and pre-storm distributions for fluctuations of the solar wind density, as characterized by the ULF power index T_N, during solar min (1995) and max (2000) for 12 hours time intervals before storm commencement.

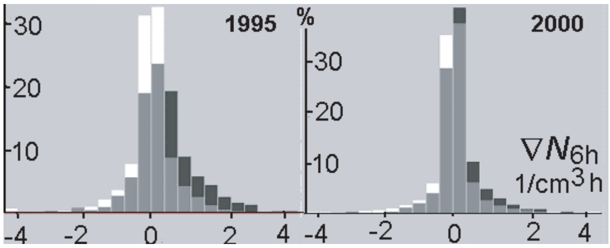

Fig. 7. Comparison of histograms of annual distributions and pre-storm distributions (12 hours before storm commencements) of hourly values of the 6-hour gradient of N for the solar minimum (1995) and maximum (2000).

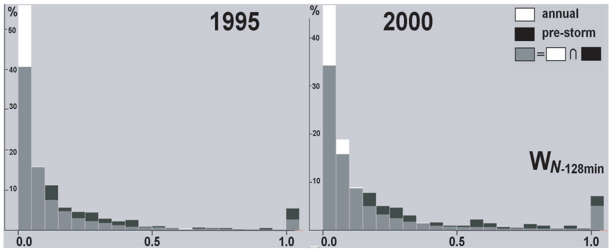

Fig. 8. Comparison of the statistical distributions of the wavelet power W_N of plasma density fluctuations with time scales 4-128 min for the whole year and for the period 12 hours before storm onsets for 1995 (left-hand panels) and 2000 (right-hand panels).

solar minimum and maximum. The power of solar wind long-period density fluctuations W_N increases $\sim$12 hours before storm onset, especially during solar maximum (1995) (Fig. 7). The same distribution for the 2-day time interval (not shown) demonstrates a substantial decrease of the effect. Thus, the solar wind density becomes more turbulent and irregular about 1 day before the main growth of N.

6. Discussion

The main problems of medium-term magnetic storm forecasting are a consequence of the shift of scientific interest to prognosis of severe magnetic storms only and toward estimation of the probability of the registration of CMEs near Earth. The most proper path toward their solution may be to search for additional prognostic factors in the solar wind. Recent work shows that variations of the solar wind plasma and IMF are a largely underestimated factor in magnetic storm triggering and could be effectively used for space weather forecasting analysis.

These studies show that the solar wind density plays a more significant geoeffective role than was previously assumed. A sharp density increase and consequent negative Bz can produce weak, moderate and even strong magnetic storms without any significant changes of the solar wind velocity. The triggering role of density is not revealed clearly with standard statistical analysis because a delay time between the rapid jump of N and Dst minimum varies substantially from storm to storm. Probably, the density increase may stimulate the release of energy accumulated in the magnetosphere, whereas V pumps instantly solar wind/IMF energy into the magnetosphere under favorable IMF orientation.

Case studies and analysis of statistical distributions have revealed some new features of the solar wind/IMF behavior several hours to days before storms. A weak irregular increase of density is observed before a storm commencement, starting, on average, $\sim$2 days before the main geoeffective density growth. The power of low-frequency solar wind density fluctuations (with time scales from $\sim$2 min to $\sim$100 min), as estimated by the wavelet power and ULF wave index, starts to grow, on average, $\sim$1 day prior to storm commencement.

Possible mechanisms of pre-storm irregular growth of the solar wind density have not been established. One possible mechanism may be related to the stream instability of solar wind plasma, resulting in the excitation of MHD waves.

Also, studies of the solar wind have revealed plasma density enhancements near the heliospheric current sheet (HCS) and high-speed corotating streams adjacent to the HCS plasma sheet [15]. Thus, a high plasma density and low velocity may be an indicator that a spacecraft and Earth are approaching the HCS region owing to the presence of naturally occurring high densities near the HCS and also to stream-stream compressive effects. The southward IMF orientation, which eventually causes moderate storms, may be related to the corotating stream interaction with the HCS and its plasma sheet.

Finally, fluctuations in active regions on the Sun, anticipating development of CMEs or solar flares, may modulate the solar wind. An investigation of the relationship between long-period pulsations of CM radio emission and solar proton flares showed an occurrence of a relationship between them. This phenomenon has been suggested for use in solar ejection forecasting [17]. Recently, indications of solar wind modulation by various modes of solar oscillations have also been found [16].

Though possible mechanisms of these phenomena have not been reliably identified yet, observed features of the solar wind plasma structure before magnetic storms may be classified as medium-term precursors, and thus could be used for forecasting purposes.

7. Conclusion

None of the methods proposed so far for magnetic storm and substorm forecasting provides sufficient accuracy and proper timing. Therefore, the space weather community should try to implement the cybernetic principle - ”to build a reliable system from non-reliable components,” and combine various forecasting tools. This study has shown that solar wind density plays a more significant geoeffective role than is usually considered. It was found that sharp density increases and consequent negative Bz excursions can produce weak, moderate and even strong magnetic storms without any significant changes in solar wind velocity.

The statistical correlations for the period 1995-2005 indicate that intrinsic properties of the solar wind and IMF, as well as their magnetospheric response, vary during a solar cycle. During solar maximum the geoeffectiveness of V drops, and geoeffectiveness of N is significant during solar minimum only. Throughout the solar cycle the geoeffectiveness of interplanetary electric field, E_{EW} and E_{EW}, has turned out to be not very high, just slightly higher than that of Bz. The correlation between N and Bz is low, but the correlation of N with $|B|$ is much higher. A remarkably high correlation between the low-frequency solar wind plasma turbulence with time scales 4-32 min and IMF magnitude $|B|$ occurs.

Case studies and analysis of statistical distributions have revealed some new features of the solar wind/IMF behavior several hours to days before storms. A weak turbulent increase of density is observed before a magnetic storm commencement, starting, on average, 2 days before the geoeffective density growth. The power of low-frequency solar wind density fluctuations (with time scales from ~ 2 min to ~ 100 min), as estimated with the wavelet technique and ULF wave power index, starts to grow, on the average, ~ 1 day prior to storm commencement. An elevated level of solar wind/IMF turbulence in the Pc5 band before storm onsets may induce enhanced ULF magnetic activity on the ground.

These features of the solar wind plasma structure before magnetic storms may be classified as medium-term precursors of magnetic storms, and thus could be used for forecasting purposes. We suggest that variations of the solar wind plasma are a largely underestimated factor in magnetic storm triggering and could be effectively used for space weather forecasting.

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