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Advances in Space Research xxx (2013) xxx–xxx

ADVANCES IN SPACE RESEARCH
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ULF wave index as magnetospheric and space-weather parameters

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Received 7 November 2012; received in revised form 6 June 2013; accepted 28 July 2013

Abstract

Waves in the Ultra Low Frequency (ULF) band owe their existence to solar wind turbulence and transport momentum and energy from the solar wind to the magnetosphere and farther down. Therefore an index based on ULF wave power could better characterize solar wind–magnetosphere interaction than K_P, Dst, AE, etc. indices which described mainly quasi-study state condition of the system. We have shown that the ULF wave index accurately characterize relativistic electron dynamics in the magnetosphere as these waves are closely associated with circulation, diffusion and energization of relativistic electrons in the magnetosphere. High speed solar wind streams also act as a significant driver of activity in the Earth's magnetosphere co-rotating interaction region and are responsible for geomagnetic activities. In the present paper, we have analyzed various cases related with very weak (quiet) days, weak days, storm days and eclipse events and discussed the utility of the ULF wave index to explain the magnetospheric dynamics and associated properties. We have tried to explain that the ULF wave index can equally be useful as a space weather parameter like the other indices.

Keywords: Magnetosphere; Solar wind; Interplanetary magnetic field (IMF); Turbulence; ULF wave index

1. Introduction

The energy transfer during the interaction of turbulent solar wind and terrestrial magnetosphere drives a number of processes and phenomena occurring in the magnetosphere, ionosphere and lower atmosphere. One of the method to characterize these interactions is the study of ULF waves, which are excited by the Kelvin–Helmholtz instability at the flank of magnetopause (Li et al., 2012), external solar wind impulses (Antonova, 2000), drift and drift-bounce resonance processes in the magnetosphere/ionosphere (Yeoman and Wright, 2001). The analysis of ground based 1–10 mHz ULF wave power, upstream solar wind speed and MeV electron flux across the outer radiation belt from the SAMNET and IMAGE arrays during the complete solar cycle period 1990–2001, show strong correlation between ULF wave power and solar wind velocity (Mann et al., 2004), and both are individually well correlated with MeV electron fluxes. ULF waves are capable of monitoring the small scale structures within the field aligned current (Scoffield et al., 2005, 2007). The Plasmasphere–magnetosphere mass loaded ion density variation from dawn to dusk and the plasmapause motion (Fraser, 2003), modulation (Yang et al., 2010) and acceleration (Zong, 2009) of the magnetospheric electrons.

The turbulent character of solar wind magnetosphere system could not be explained by the usual geomagnetic indices such as AE, Au, AL, K_p, Dst and polar cap index (PCI), which were developed to characterize the quasi-steady state level electrodynamics of near-Earth environment. This leads to the introduction of a ULF wave power index (Kozyreva et al., 2004) which could conveniently describe the turbulent character of solar wind–magnetosphere system (Romanova et al., 2007). Using the ULF wave index, it has been verified that when the solar wind is more turbulent, the effective degree of its coupling to

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http://dx.doi.org/10.1016/j.asr.2013.07.040

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the magnetosphere is higher (Borovsky and Funsten, 2003; Romanova et al., 2007) and the level of IMF turbulence does not depend on IMF north south orientation. ULF wave indices have also been found useful in the study of relativistic electron dynamics (Kozyreva et al., 2007; Romanova et al., 2007; Romanova and Pilipenko, 2009) and space weather applications (Pilipenko et al., 2007; Singh et al., 2010, 2011).

In this paper, we have analyzed the ULF wave index data and have discussed its relevance in the characterization of solar wind–magnetosphere coupling and the associated magnetospheric plasma dynamics. The correlation of ULF wave index with relevant space weather parameters, viz., solar wind velocity (V), noise spectral power (Np), z component of IMF Bz, Dst, K_p etc. for few very weak (quiet) storm, weak storm, and super storm events are analyzed and discussed.

2. Construction of ULF wave index

The usual geomagnetic indices characterized the quasi study state level of the involved phenomena and the effects introduced by the presence of turbulence of the solar wind/ magnetosphere system remain uncharacterized. In order to overcome this limitation ULF wave index is introduced (Kozyreva et al., 2007), which depends upon the ULF wave power and hence includes turbulence of the solar wind magnetosphere system. The index is constructed using the hourly averaged spectral wave power in Pc 5 wave frequency band based on data from a global array of stations. The spectral power density $[B_f^2(\mathrm{nT}^2/\mathrm{Hz})]$ in the selected frequency band is computed for the two horizontal components of the wave field. The discrete Fourier Transform technique is used to evaluate the integrals of oscillatory functions in a one hour window.

The ULF wave power in the frequency band $\Delta f = f_H - f_L$, averaged over two horizontal components for the ith station in the unit nT is written as

$$P_i = \frac{1}{2}\left[\Delta f \sum_{j=1,2} \int_{f_L}^{F_H} B_i(f)df\right]^{1/2} \quad (1)$$

where f_L and f_H are the lower and higher frequency of the band. If there are Nst number station which recorded ULF waves having a signal power above a certain threshold value (Kozyreva et al., 2007) then ULF wave power is obtained by averaging the computed power from each station which is written as

$$P = \frac{1}{Nst}\sum_{i=1}^{Nst} Pi \quad (2)$$

The ULF wave power P represents the ULF wave index in nT. Earlier ULF index was $(\mathrm{nT})^2/\mathrm{Hz}$, similar to the spectral power density. The details of the limitations and computational techniques are given by Kozyreva et al. (2007) and Romanova et al. (2007).

3. Relation between relativistic electron dynamics and ULF wave index

The relativistic electrons in the inner magnetosphere cause environmental impacts, affect space hardware in the Medium Earth Orbits (MEOs) and Geostationary Earth Orbits (GEOs) and have effects upon the space weather (Friedel et al., 2002). The enhancements of these electrons are observed to associated with magnetic storms (Reeves, 1998), although same events are reported to occur without a storm or during a mild storm. Out of various mechanisms proposed to explain the relativistic electron dynamics in the outer radiation belt (Friedel et al., 2002), ULF waves in the Pc 5 band have emerged as an important source of energy to the relativistic electrons (O'Brien et al., 2001). Theoretical mechanisms attributed to MeV electron acceleration by the action of ULF wave fields include; enhanced radial diffusion in ULF wave electric fields (Elkington et al., 2001), magnetic pumping (Liu et al., 1999); transit time acceleration in compressional ULF waves (Summers and Ma, 2000), etc. Mann et al. (2004) showed that the relativistic electron flux variations are well correlated with the solar wind velocity and the ULF wave power at high L-shells. The correlations were found to be very high during the late declining phase of the solar cycle. Further, the ULF wave power measured from the ground station between $L = 3$ and 6.6 was found to be most correlated with the MeV electron flux at GEO, independent of the L-shell of the ground station, although the magnitude of the wave power itself remains a strong function of L value.

Studies have shown that relativistic electron enhancements may be linked to intervals of enhanced and sustained ULF activity in the magnetosphere (Baker et al., 1998; Rostoker et al., 1998; Mathie and Mann, 2000; Romanova et al., 2007). The enhanced level of ULF wave activity precedes the peak of relativistic electron flux for two to four days. This time delay implies the cumulative effect of radial diffusion process to over all relativistic electrons enhancements. Thus, the long lasting ULF wave activity is more important for the relativistic electron bursts than instant intense bursts of wave activity. As relativistic electron enhancements are observed to be well correlated with the solar wind velocity, we have computed and shown the variation of ULF wave index with the solar wind velocity (Fig. 4), which increases with the increase in solar wind velocity. The correlation coefficient is 0.25.

4. ULF wave index and magnetospheric dynamics

The presence of turbulence in the solar wind plays effective role in the degree of its coupling with the magnetosphere. Therefore the presence of turbulence should have profound effects on the large scale dynamics of the magnetospheric system. This arises through eddy velocity and diffusion. Turbulence also affects the ULF wave amplitude. At high latitudes ULF frequencies match the fundamental Eigen frequency of shear standing Alfven waves between the conjugate ionospheres along magnetic field lines stretched into the magneto tail (Rankin et al., 2000; Lui and Cheng, 2001). These waves can also be interpreted as a manifestation of internal magnetospheric phenomena like shear Alfven field line resonances (FLRs) and global magnetospheric cavity/waveguide waves (Samoson et al., 1992; Walker et al., 1992). Borovsky and Gosling (2001) have explained that the geomagnetic activity occurring across the magnetospheric regions is related with the amplitude of MHD turbulence in the solar wind. Borovsky et al. (1998) tried to simulate solar wind–magnetosphere interaction in terms of flowing fluid interaction with an object.

The upstream turbulence produces eddy viscosity of the fluid (Borovsky and Funsten, 2003), which along with the molecular viscosity is coupled to obstacles (Wu and Faeth, 1994; Volino, 1998). This correlates with the idea that the high Reynolds number fluid experiments are complementary to low Reynolds number MHD simulation. As the amplitude of solar wind turbulence increases, the viscous interaction between solar wind and magnetosphere increases. An enhanced upstream turbulence causes more momentum transfer from the magnetosheath into the magnetosphere, resulting in more stirring of the magnetosphere and this causes more geomagnetic activity. Thus, correlations between the turbulence and geomagnetic activity indices such as AE, AU and AL (Rostoker, 1972) and Polar Cap Index PCI (Troishichev et al., 1988) and K_p, Dst

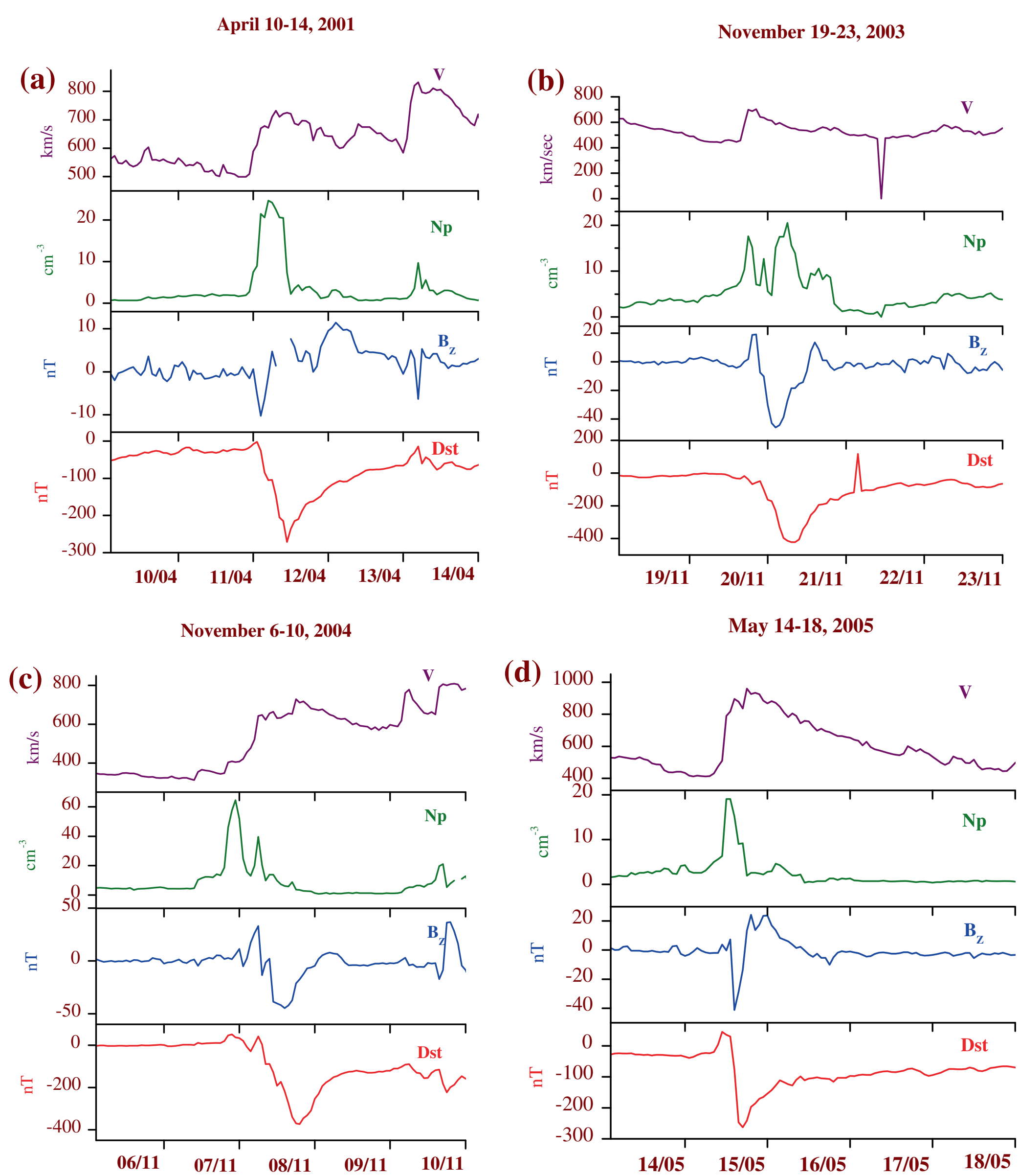

Fig. 1. Variations in the solar wind parameters (velocity V, density Np, IMF Bz, Dst) for four magnetic super storm days.

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and Ap (Mayaud, 1980) are established. Some of the important physical consequences of the approach are:

(a) The correlations are owed to a filter-effect wherein DC electric fields of the solar wind are filtered and AC electric field components penetrate into the magnetosphere (Garrett et al., 1974). Thus, when the fluctuations are larger the magnetosphere is driven harder by the solar wind.
(b) The fluctuations produce locally enhanced surface currents at the magnetopause that drives the magnetic field line reconnection harder (Schindler, 1979). More turbulent solar wind results in a higher degree of coupling to the magnetosphere, which has also been confirmed by the ULF wave index (Pilipenko et al., 2007). Under southward IMF condition ($Bz < 0$), AE grows linearly with an increase of |Bz|, whereas for the northward condition ($Bz > 0$), the average AE values do not strongly depend on the solar wind driver (Borovsky and Funsten, 2003).

The role of solar wind parameters on the magnetospheric dynamics is illustrated with the help of Fig. 1(a)–(d). Which show the variations in the solar wind parameters (velocity and density) and Bz component of the IMF for the four analyzed super storms based on OMNI database (http://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni/high_res_omni/). The Dst variation shows the different phases of geomagnetic storms. It is seen that, first, a compression region with a high solar-wind density (up to 60 cm^{-3}) approaches the Earth's magnetosphere, leading to development of the initial phase of magnetic storm. The

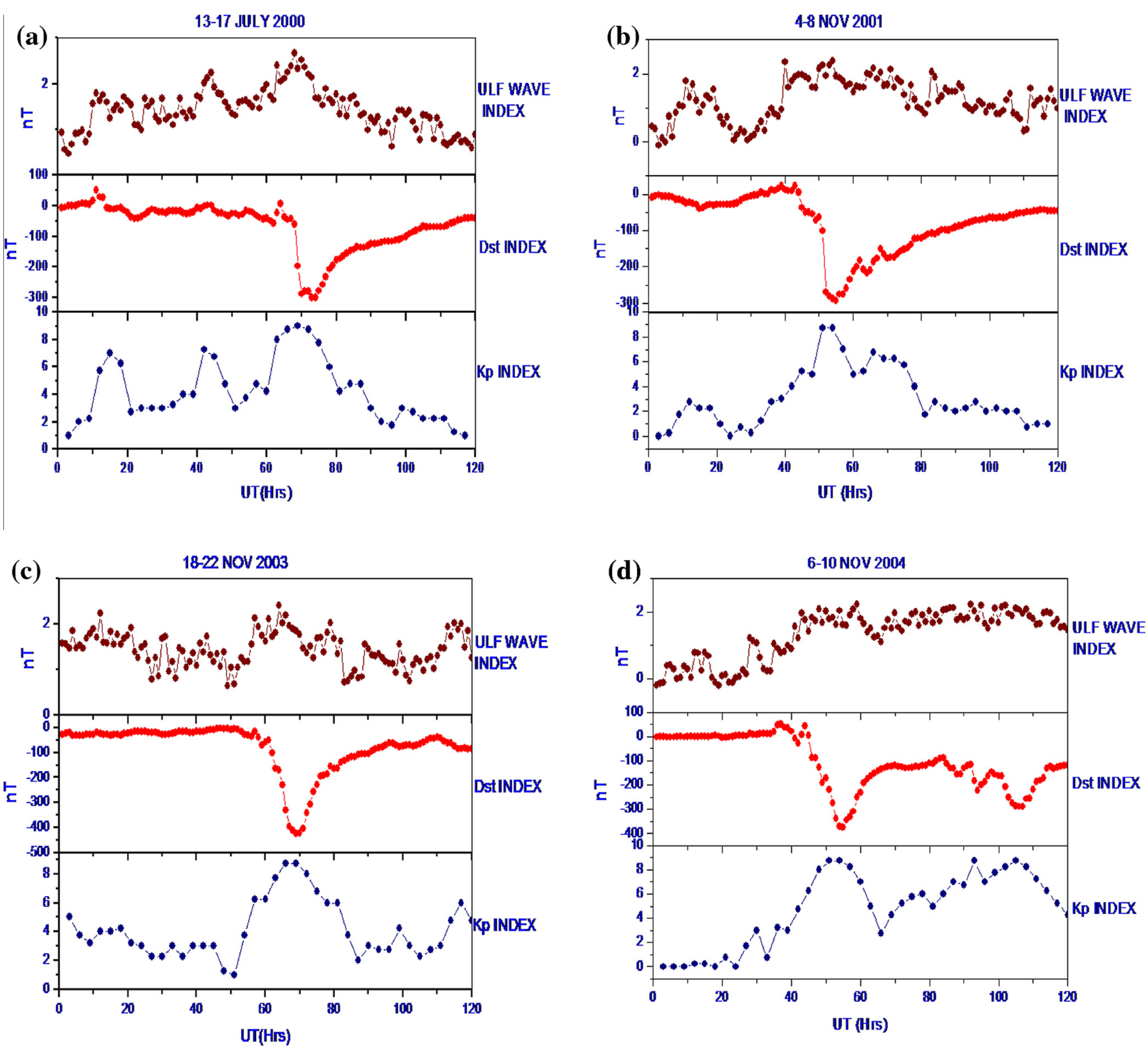

Fig. 2. Variations of K_p, Dst and ULF wave index during storm periods.

compression region is followed by a high velocity stream (∼300–800 km/s) with a low solar wind density. Such a variation in the solar wind parameters substantially differs from their behavior during CME events or magnetic clouds (Burlaga et al., 1981; Kozyreva et al; 2004), where a sharp increase in the solar wind density and velocity takes place simultaneously, as was observed during the magnetic storm of May 14–18, 2005 (Fig. 1d). It is also seen that in Fig. 1(b, c, and d) that CIR storms are characterized by variations in the Bz values of the IMF, which varied during a few hours from −40 to +20 nT. The large negative values of the Bz of the IMF were not observed for long-duration time intervals (longer than 3 h). On the contrary, the sign of the Bz component of the IMF remained constant for more than a day (Fig. 1b). For all these super storms, the K_p index varied between 8 and 9, whereas the characteristic features such

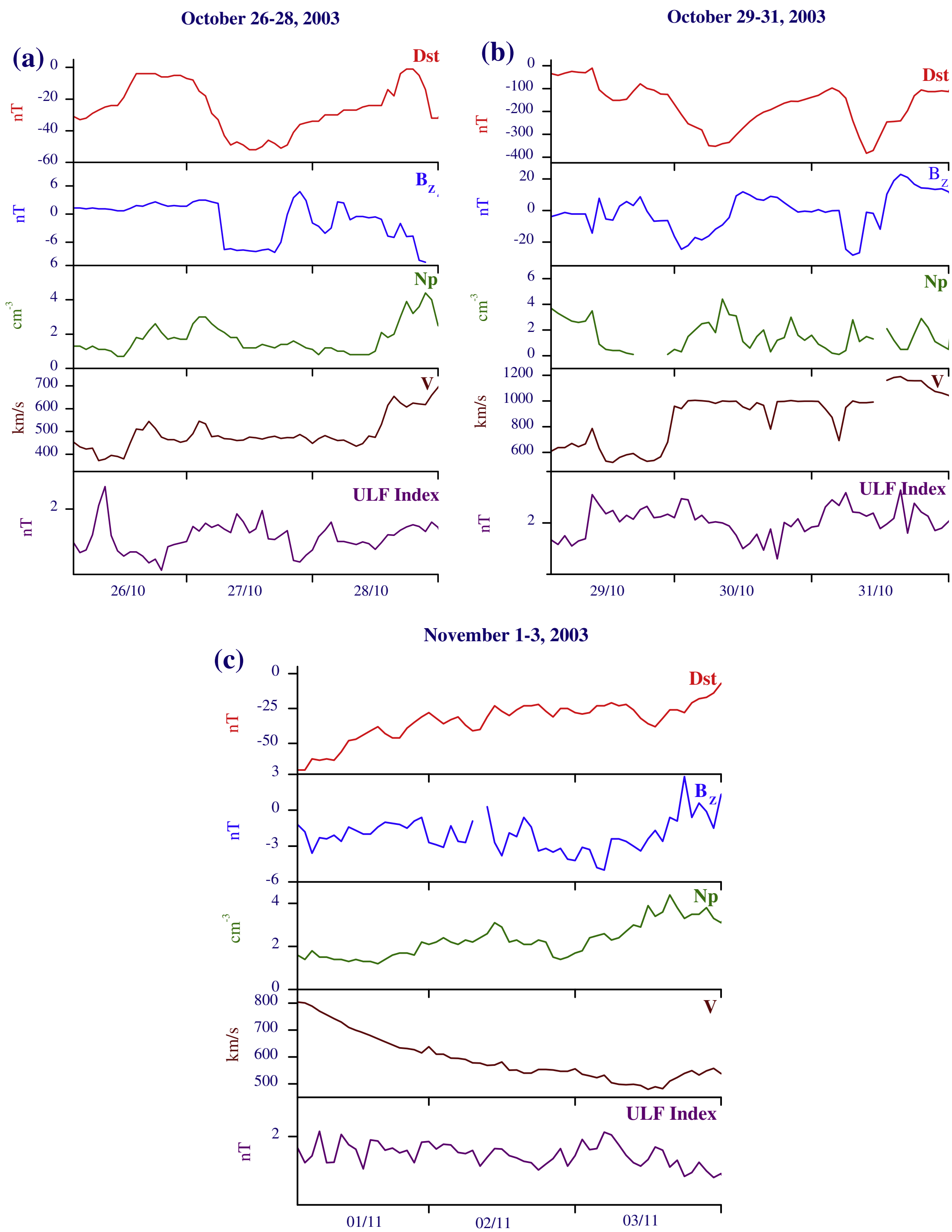

Fig. 3. Examples of variation in ULF wave index, Velocity (V) and Density (Np) of solar wind, Bz component of IMF and Dst index during (a) weak storm days, (b) super storm days and (c) very weak storm (quiet) days.

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as the Dst values, main phase duration and recovery time etc. varied. The corresponding ULF wave index for these storms shown in Fig. 1a–d, is 2.33, 2.19, 2.36 and 2.02 respectively. We present another set of super storms in figure (2a–d) in which the variations of the ULF wave index, Dst index and K_p index are shown. During the magnetic storm K_p index increases and the Dst index decreases. The ULF wave index increases. But there is no linear relationship between ULF wave index and Dst index or K_p index.

Fig. 2a, c show that ULF wave index becomes maximum during the main phase of the magnetic storm. This means that the ULF wave activity enhances at the time of the main phase and the recovery phase ULF activity decreases. If there occur sub storms in the recovery phase (2b, d) then ULF wave activity remains high even during the recovery phase of the geomagnetic storm. Analyzing moderate magnetic storms (Dst varying between -150 and -100 nT) using the ULF wave index activity, Kozyreva and Kleimenova (2008) reported that the intensity of ULF wave activity is maximal during the main phase of the magnetic storm rather than during recovery phase as it was considered previously.

The shape of Dst variations during CIR storms is not classical, as in the case with CME storms, and very often it is difficult to identify the time boundary between the main and the recovery phases of a storm as can be seen from Fig. 2(a)–(d). The time interval after the minimal Dst indices are reached, when $d\mathrm{Dst}/dt$ becomes >0, is usually attributed to the recovery phase of a magnetic storm. Two stages are often identified in the time dynamics of the Dst index, namely, an early fast stage and a late slow one. At the late stage of recovery, the Bz component of the IMF becomes positive and the solar wind energy stops entering the magnetosphere. However, such division of the magnetic storm recovery phase into two stages clearly can only be done for CME storms. A substantial difference in the variations of the solar wind parameters and IMF for CIR and CME storms is likely to show up as different wave responses of the magnetosphere to external actions.

5. ULF wave index as a proxy to space weather parameter

ULF waves, generated via drift instabilities are transmitted from the magnetosphere through the ionosphere to the ground (Pilipenko, 1990). In this process, the solar wind velocity is the only controlling factor of IMF wave turbulence that also controls the ground based ULF activity (Engebretson et al., 1998). This is confirmed by the correspondence between the hourly values of ground ULF wave index and solar wind velocity (Romanova and Pilipenko, 2009; Pahud et al., 2009). The ULF wave power increases with increase of velocity and growth becomes less steep for high velocity solar wind. The solar wind magnetic field component Bz controls the reconnection and particle injection processes and also contributes to the generation of magnetospheric ULF wave activity. The asymmetry of correlation function of the ULF activity and solar wind velocity shows that the shear flow instability is not the only mechanism to excite ULF waves, but the solar wind plasma density enhancements also contribute into the ULF wave excitation which is also supported by the observations (Engebretson et al., 1998; Kleimenova et al., 2003). These discussions briefly show that the proposed ULF wave index could also explain geomagnetic disturbances which are the result of turbulent be linked to solar wind interaction with the magnetosphere and thus ULF waves index could the space weather phenomena.

In order to link ULF wave index with the various parameters of solar wind, we consider very weak (quiet), weak and super geomagnetic storms which are shown in Fig. 3. The variations in the Dst index, IMF Bz component, solar wind density (Np) and velocity (V), and surface ULF index are shown. Sudden commencement of magnetic storms (Fig. 3a–c) was characterized by a considerable jump of the solar wind density and velocity and was accompanied by an abrupt increase in the ULF index (the pulsation amplitude increased by more than an order of magnitude in this case). It is important to see that all the three considered storms developed when solar wind density is very low ($\sim$4 cm^{-3}) and average velocity is ($\sim$450–650 km/s). Even the IMF Bz is relatively quite small except in the case of super storms (3b). The southward turning of the IMF Bz component and the development of the magnetic storm main phase were accompanied by a gradual increase in the ULF index in all the considered cases in spite of low values of the solar wind density (Fig. 3a and b). During the main phase of the magnetic storms shown in Fig. 3c the value of the solar wind velocity remained large; however the value of the ULF index was approximately identical during the main phase of all three considered events. However, the

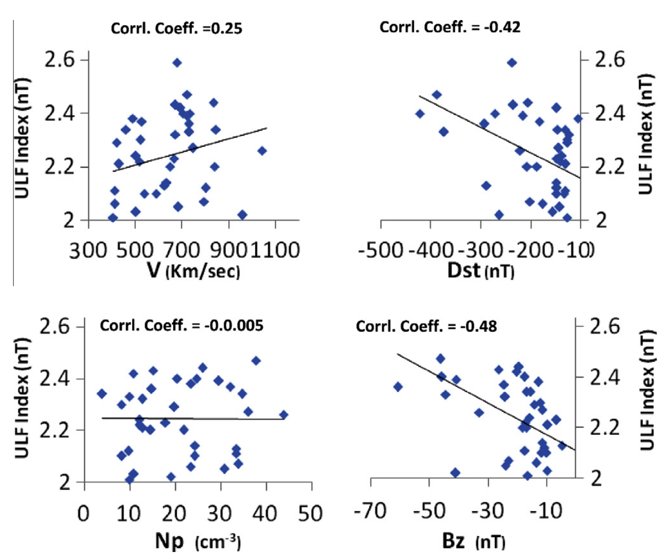

Fig. 4. Variation (scattered plot) of ULF wave index with the solar wind velocity, density, IMF Bz and Dst. Derived correlation coefficient is also shown on the figure.

appearance of individual intervals with negative IMF Bz values during this storm phase was accompanied by a short term increase in the ULF index (Fig. 3b and c). It is apparent that a gradual increase in the solar wind velocity did not result in an increase in the wave activity.

We have considered 40 storm days during year 1997–2009 and computed ULF wave index. The variations of ULF wave index with the solar wind parameters such as Dst, IMF Bz, solar wind velocity (V) and density (Np) are shown in Fig. 4. It is seen that ULF index decreases with Dst and Bz and the correlation coefficient is −0.42

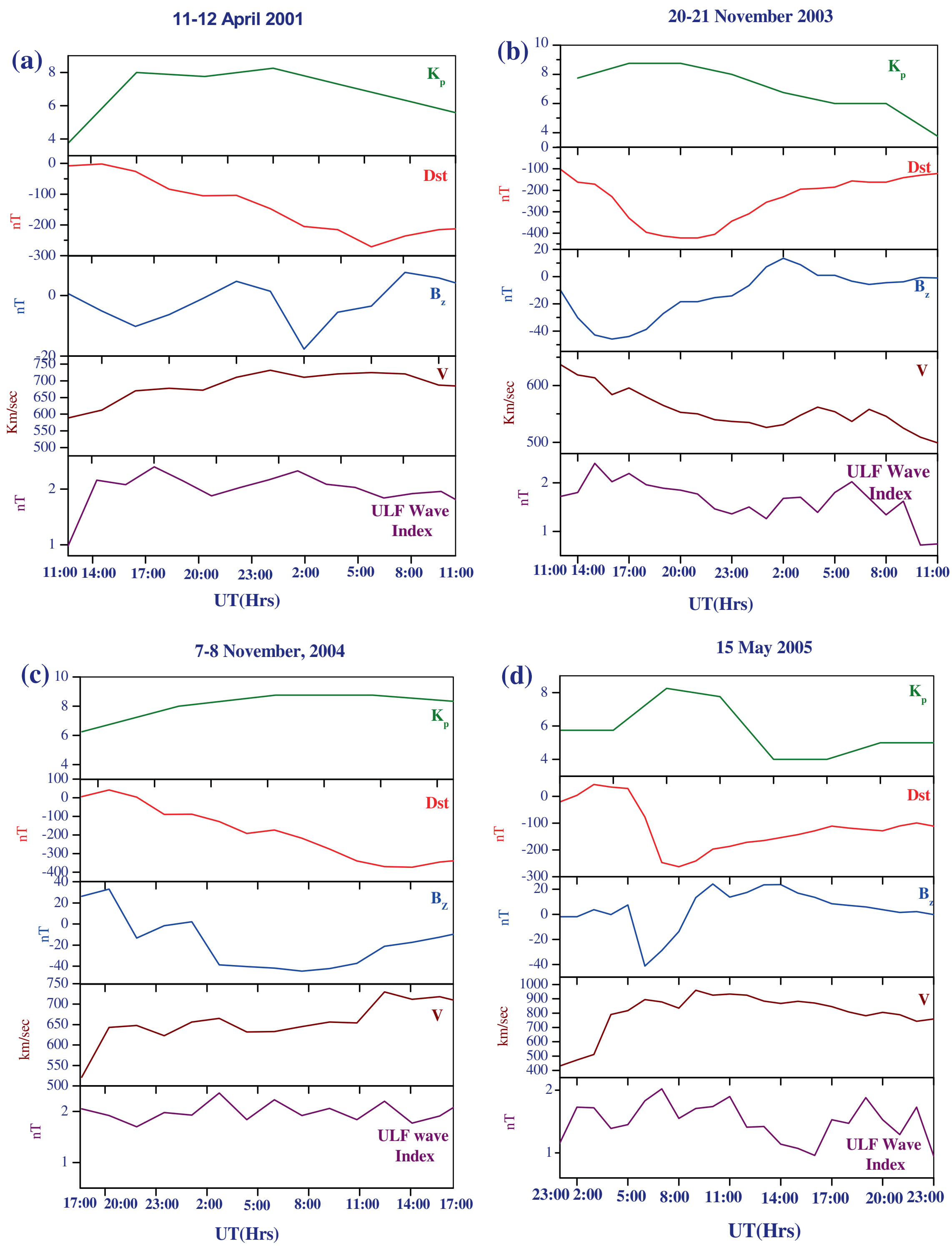

Fig. 5. Variation of space weather parameters (K_p index, Dst index, solar wind magnetic field Bz, solar wind velocity V) with ULF wave index observed on (a) April 11–12, 2001, (b) November 20–21, 2003, (c) November 7–8, 2004, (d) May 15, 2005.

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and −0.48 respectively. The variation with solar wind density does not show statistically significant correlation (Correlation coefficient = −0.005). Solar wind velocity show a positive correlation (Correlation coefficient = 0.25). The details of ULF wave index variation during different phases of magnetic storms for four selected super storms are given in Fig. 5. The selection is based on the basis of minimum Dst index. The first selected case of super storm occurred on April 11–12, 2001 during 11.00 h of April 11–11.00 h of April 12, 2001 (Fig. 5a). Dst value very slowly decreases from almost zero value to −271 nT during almost 20 h. During this period K_p index rises from 4, reached 8+ remained constant and then decreases to 5. The ULF wave index during this period varies between 0.98 and 2.33 nT. The high value of ULF wave index again supports the conditions of super storm days. We can also discuss the relationship between ULF wave index and various solar wind parameters such as solar wind velocity and Bz. When

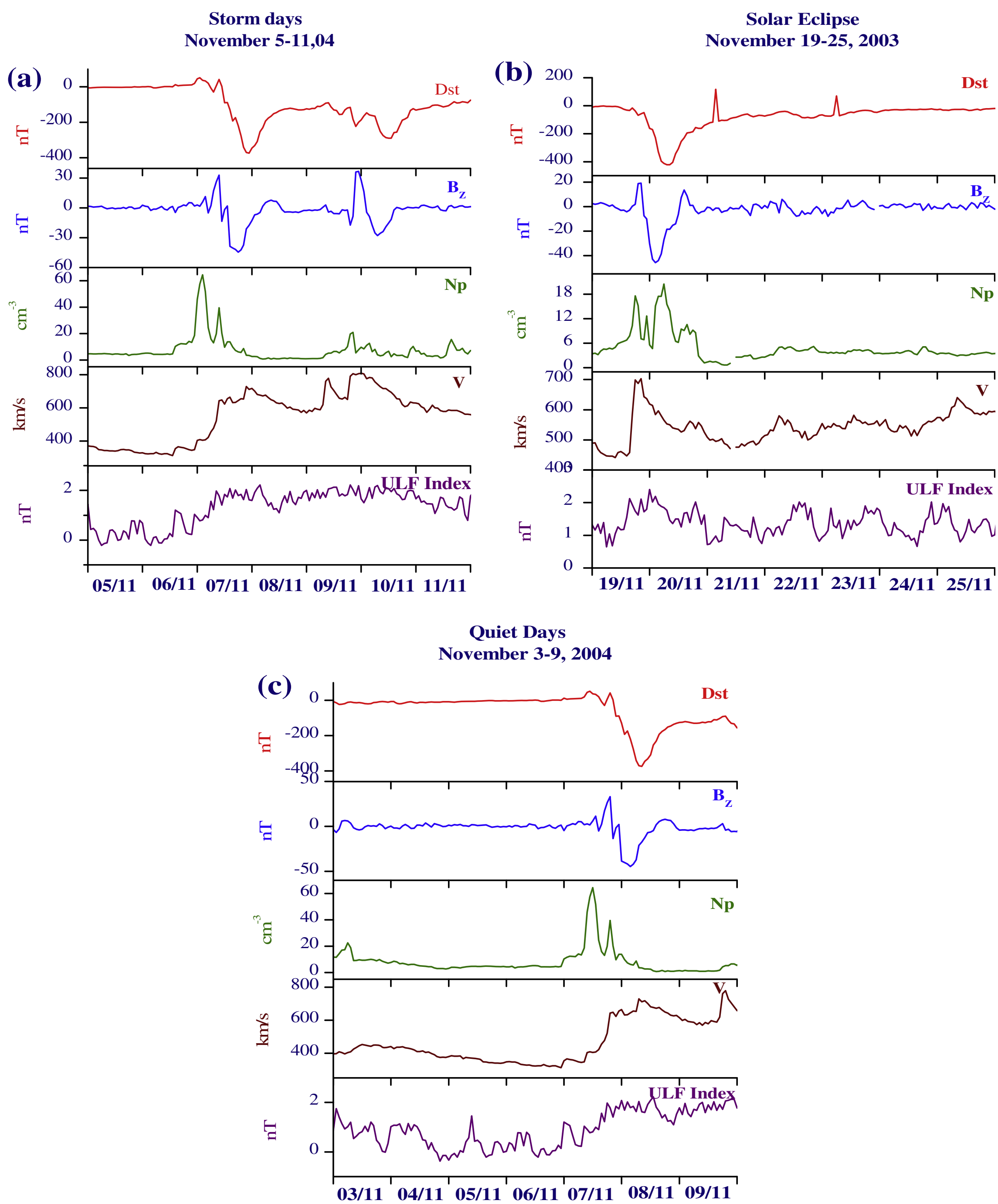

Fig. 6. Examples of variation in ULF wave index, Velocity (*V*) and Density (Np) of solar wind, Bz component of IMF and Dst index during (a) storm (b) eclipse and (c) quiet days.

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the solar wind velocity varied between 499 and 725 km/s, Bz lies between −10.2 and +10.2 nT, the ULF wave index attains the maximum value of 2.33 nT.

The second selected case is of November 20–21, 2003 during 11.00 h of November 20–11.00 h of November 21, 2003 (Fig. 5b). The K_p index smoothly varies between 4^- and 9^-, while the Dst varied from −422 and −49 nT. The ULF wave index varied between 0.72 and 2.19 nT. It is interesting to note that small peaks in the solar wind velocity are well represented by the peaks in the ULF wave index. The solar wind velocity varied between 499 and 643 km/s. The Bz lies between −45.9 and 13.5 nT. Fig. 5(c) shows the variation of space weather parameters from 1700 UT, November 7–1700 UT, November 8, 2004. The K_p index slowly increases from 6^+ and reaches to 9^- and thereafter remains almost constant, while the Dst index varied between −373 and 42 nT. The ULF wave index varied between 1.72 and 2.36 nT. The variation in solar wind velocity was between 521 and 730 km/s, Bz lies between −44.6 and 33 nT. During the entire period, ULF wave index fluctuates around 2. This is understandable because the Dst decrease shows that this whole period (∼20 h) correspond to transition from the initial phase to the main phase of the geomagnetic storm. The next example corresponds to may 15, 2005 (Fig. 5d). In this case Dst index was <263 nT and K_p index varied between 4 and 8^+. The ULF wave index varied between 0.73 and 2.02 nT and showed peaks during the initial, main and recovery phases of the storm. The variation in solar wind velocity was between 414 and 959 km/s, Bz varied between −41.2 and 24.2 nT.

Fig. 6a–c show variations of Dst, Bz, solar wind density and velocity and ULF index for disturbed day, solar eclipse day and quiet days. It can be seen that a compression region with a high solar wind density (up to 60 cm^{-3}) approaches the Earth's magnetosphere leading to development of initial phase of magnetic storm (Fig. 6a, c). The compression region is followed by a high velocity stream (∼700 km/s) with low solar wind density. This variation in the solar wind parameters substantially differs from their behavior during CME events where a sharp increase in the solar wind density and velocity takes place simultaneously (Kozyreva et al., 2004).The ULF wave index increases during initial and main phase of the storm and show decrement during the recovery phase. However, when velocity enhances during the recovery phase then ULF index remains at higher values. In the case of solar eclipse event (Fig. 6b), the solar wind density and velocity remains high simultaneously during the main phase of the storm. Although density varies between 6 and 20 cm^{-3}, but velocity jumps from 480 to 700 Km/s. After the recovery of the storm density decreases below 6 cm^{-3} and velocity remains below 600 Km/s. The ULF index shows broad peak during the main phase. The solar wind velocity variation is clearly visible in the ULF index. These results show that the ULF index variations are correlated with solar wind parameters associated with space weather events.

6. Summary/Conclusions

The energy coupling during the solar wind interaction with the Earth's magnetosphere under the quasi steady state condition can be statistically described by the geomagnetic indices (K_p, Dst, AE, etc.) and averaged solar wind/IMF parameters. The quasi steady state condition does not involve turbulence present in the solar wind and the magnetosphere. The ULF waves propagating from the magnetopause to the Earth's surface via the magnetosphere and ionosphere involve turbulence present in the system. Therefore, an index derived from the ULF wave power could better represent the processes involving in the interaction of solar wind with the magnetosphere. We have analyzed a large number of cases and studied different phenomena in the magnetosphere and discussed their relation with ULF wave index.

The results show that the solar wind velocity is positively correlated with the ULF wave index. Observation revealed direct correlation between relativistic electron enhancement and solar wind velocity. Therefore, it is argued that ULF index could easily predict/explain the enhancement of relativistic electron bursts observed in the magnetosphere. While discussing the magnetospheric dynamics under the impact of geomagnetic storm, we have shown that during the super storm, the ULF wave index is maximum in the main phase of the storm. However, during the recovery phase if sub storms occur then ULF index does not decrease and remains high. We have also studied the relation between ULF index and solar wind/IMF parameters. The results show that the ULF index is uncorrelated with the solar wind density, whereas it correlates negatively with the Dst and Bz. Finally we may conclude that the ULF wave power index derived from ground and satellite data can be of great assistance in statistical study of space weather phenomena and solving various space physics problems and it can be treated both as an important magnetospheric parameter as well as a space weather parameter.

Acknowledgements

AKS is thankful to Department of Science and Technology, Government of India, for providing financial support as research project. Authors are also thankful to ISRO, Government of India for providing partial financial support under CAWSES phase–II program.

References

Antonova, E.E. Large-scale magnetospheric turbulence and the topology of magnetospheric currents. Advances Space Research 25, 1567, 2000.

Baker, D.N., Pulkkinen, T.I., Li, X., Kanekal, S.G., Ogilvie, K.W., Lepping, R.P., Blake, J.B., Callis, L.B., Rostoker, G., Singer, H.J., Reeves, G.D. A strong CME-related magnetic cloud interaction with the Earth's magnetosphere: ISTP observations of rapid relativistic electron acceleration on May 15, 1997. Geophysical Research Letter 25, 2975, 1998.

Borovsky, J.E., Gosling J.T., The level of turbulence in the solar-wind and the driving of the Earth's magnetosphere, J Eos Trans. AGU, 82, 20 Spring Meet. Suppl. S368, 2001.

Borovsky, J.E., Funsten, H.O. Role of solar wind turbulence in the coupling of the solar wind to Earth's magnetosphere. Journal of Geophysical Research 108, 1246, 2003.

Borovsky, J.E., Thomsen, M.F., Elphie, R.C. Driving of the plasma sheet by the solar wind. Journal of Geophysical Research 103, 617, 1998.

Burlaga, L.F., Sittler, E., Mariani, F., Schwenn, R. Magnetic loop behind an interplanetary shock: voyager, helios, and IMP 8 observations. Journal of Geophysical Research 86, 6673–6684, 1981.

Elkington, S.R., Hudson, M.K., Chan, A.A. Acceleration of relativistic electrons via drift resonant interaction with toroidal-mode Pc-5 ULF oscillations. Geophysical Research Letter 26, 3273, 2001.

Engebretson, M., Glassmeier, K.H., Stellmacher, M., Hughes, W.J., Luhr, H. The dependence of high latitude Pc5 wave power on solar wind velocity and on the phase of high speed solar wind streams. Journal of Geophysical Research 103, 26271, 1998.

Fraser, B.J. Recent developments in magnetospheric diagnostics using ULF waves. Space Science Review 107, 149, 2003.

Friedel, R.H.W., Reeves, G.D., Obara, T. Relativistic electron dynamics in the inner magnetosphere a review. Journal of Atmospheric and Solar-Terrestrial Physics 64, 265, 2002.

Garrett, H.B., Dessler, A.J., Hill, T.W. Influence of solar wind variability on geomagnetic activity. Journal of Geophysical Research 79, 4603, 1974.

Kleimenova, N.G., Kozyreva, O.V., Schott, J.J., Bitterly, J., Ivanova, P. Dayside geomagnetic Pc5 pulsations in the conditions of a strongly disturbed solar wind during the Magnetic storm on 21 Febraury, 1994. International Journal of Geomagnetism Aeronomy 3, 229, 2003.

Kozyreva, O.V., Kleimenova, G. Estimation of storm-time level of day-side wave geomagnetic activity using a new ULF index. Geomagnetism and Aeronomy 48, 491–498, 2008.

Kozyreva, O.V., Pilipenko, V.A., Engebretson, M.J. Yumoto, Ko, Comparison of a ULF Wave Index With Dynamics of Geostationary Relativistic Electrons During Space Weather Month, American Geophysical Union, Spring Meeting, 2004

Kozyreva, O., Pilipenko, V., Engebretson, M.J., Yumoto, K., Watermann, J., Romanova, N. In a search of a new ULF index: comparison of Pc5 Power with dynamics of geostationary relativistic electrons. Planetary and Space Science 55, 755, 2007.

Li, W.Y., Guo, X.C., Wang, C. Spatial distribution of Kelvin–Helmholtz instability at low-latitude boundary layer under different solar wind speed conditions. Journal of Geophysical Research 117, A08230, http://dx.doi.org/10.1029/2012JA017780, 2012.

Liu, W.W., Rostoker, G., Baker, D.N. Internal acceleration of relativistic electrons by large-amplitude ULF pulsations. Journal of Geophysical Research 104, 17391, 1999.

Lui, A.T.Y., Cheng, C.Z. Resonance frequency of stretched magnetic field lines based on a self-consistent equilibrium magnetosphere model. Journal of Geophysical Research 106, 793, 2001.

Mann, I.R., O'Brien, T.P., Milling, D.K. Correlations between ULF wave power, solar wind speed, and relativistic electron flux in the magnetosphere: solar cycle dependence. Journal of Atmospheric and Solar-Terrestrial Physics 66, 187, 2004.

Mathie, R.A., Mann, I.R. A correlation between extended intervals of ULF wave power and storm-time geosynchronous relativistic electron flux enhancements. Geophysical Research Letter 27, 3261, 2000.

Mayaud, P.N., Derivation, Meaning and Use of Geomagnetic Indices, AGU Washington D.C., 1980.

O'Brien, T.P., McPherron, R.L., Sornette, D., Reeves, G.D., Friedel, R., Singer, H.J. Which magnetic storms produce relativistic electrons at geosynchronous orbit? Journal of Geophysical Research 106, 15533, 2001.

Pahud, D.M., Rae, I.J., Mann, I.R., Murphy, K.R., Amalraj, V. Ground based Pc5 ULF wave power: solar wind speed and MLT dependence. Journal of Atmospheric and Solar-Terrestrial Physics 71, 1082, 2009.

Pilipenko, V., Romanovo, N., Simms, L., ULF wave power index for space weather applications. WG-3 science session, Sofia MC meeting, 21–25 May, 297, 2007.

Pilipenko, V. ULF waves on the ground and in space. Journal of Atmospheric and Solar-Terrestrial Physics 52, 1193, 1990.

Rankin, R., Fenrich, F., Tikhonchuk, V.T. Shear Alfven waves on stretched magnetic field lines near midnight in Earth's magnetosphere. Geophysical Research Letter 27, 3265, 2000.

Reeves, G.D. Relativistic electrons and magnetic storms: 1992–1995. Geophysical Research Letter 25, 1817, 1998.

Romanova, N., Pilipenko, V., Crosby, N., Role of ULF wave activity in solar wind magnetosphere interactions and magnetospheric electrons acceleration, in: Physics of Auroral phenomena, Proc. XXX Annual Seminar, Apatity, 111, 2007.

Romanova, N., Pilipenko, V. ULF wave indices to characterize the solar wind magnetosphere interaction and relativistic electron dynamics. Acta Geophysicae 57, 158, 2009.

Rostoker, G. Geomagnetic indices. Review Geophysics Space Physics 10, 935, 1972.

Rostoker, G., Skone, S., Baker, D.N. On the origin of relativistic electrons in the magnetosphere associated with some geomagnetic storms. Geophysical Research Letter 25, 3701, 1998.

Samoson, J.C., Harrold, B.G., Ruohoniemi, J.M., Walker, A.D.M. Field line resonances associated with MHD waveguides in the magnetosphere. Geophysical Research Letter 19, 441, 1992.

Schindler, K. On the role of irregularities in plasma entry into the magnetosphere. Journal of Geophysical Research 84, 7257, 1979.

Scoffield, H.C., Yeoman, T.K., Wright, D.M., Milan, S.E., Wright, A.N., Strangeway, R.J. An investigation of the field aligned currents associated with a large scale ULF wave using data from CUTLASS and FAST. Annales Geophysicae 23, 487, 2005.

Scoffield, H.C., Yeoman, T.K., Wright, D.M., Milan, S.E., Wright, A.N., Strangeway, R.J. An investigation of the field-aligned current associated with a large scale ULF wave in the morning sector. Planetary and Space Science 55, 770, 2007.

Summers, D., Ma, C.Y. Rapid acceleration of electrons in the magnetosphere by fast-mode MHD waves. Journal of Geophysical Research 105, 15887, 2000.

Singh, A.K., Singh, D., Singh, R.P. Space weather: physics, effects and predictability. Surveys Geophysics 31, 581–638, 2010.

Singh, A.K., Mishra, S., Dohare, S.K. Role of ULF wave index in space weather studies. Nava Gavesana 2, 13–23, 2011.

Troishichev, O.A., Andrezen, V.G., Bennerstorm, S., Friis-Christensen, E. Magnetic activity in the polar cap – a new index. Planetary and Space Science 36, 1095, 1988.

Volino, R.J. A new model for free-stream turbulence effects on boundary layers. Journal of Turbomachinery 120, 613, 1998.

Walker, A.D.M., Ruohoniemi, J.M., Baker, K.B., Greenwald, R.A. Spatial and temporal behaviour of ULF pulsations observed by the Goose bay HF radar. Journal of Geophysical Research 97, 187, 1992.

Wu, J.S., Faeth, G.M. Sphere wakes at moderate Reynolds numbers in a turbulent environment. AIAA Journal 32, 535, 1994.

Yang, B., Zong, Q.G., Woorg, Y.F., Fu, S.Y., Song, P., Fu, H.S., Korth, A., Tian, T., Reme, H. Cluster observations of simultaneous resonance interactions of ULF waves with energetic electrons and thermal ion species in the inner magnetosphere. Journal of Geophysical Research 115, A02214, 2010.

Yeoman, T.K., Wright, D.M. ULF waves with drift resonance and drift-bounce resonance energy sources as observed in artificially-induced HF radar backscatter. Annales Geophysicae 19, 159–170, 2001.

Zong, Q.G. Energetic electrons response to ULF waves induced by interplanetary shocks in the outer radiation belt. Journal of Geophysical Research 114, A10204, 2009.

Please cite this article in press as: Singh, A.K., et al. ULF wave index as magnetospheric and space-weather parameters. J. Adv. Space Res. (2013), http://dx.doi.org/10.1016/j.asr.2013.07.040