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SUBSTORM ACTIVITY AND SHOCK WAVE FRONT ORIENTATION FOR INTERPLANETARY MAGNETIC CLOUDS

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Introduction

The solar wind magnetic clouds are manifestations of solar activity causing the most noticeable geomagnetic disturbances. This is due to the fact that they are distinguished by the presence of regions with a strong regular IMF and sharp fronts. Studies have shown that in many cases the body of a magnetic cloud is preceded by a shock wave on the leading edge of the cloud. In this case, a turbulent sheath between the shock wave and the leading edge of the magnetic cloud is detected. So it is interest to study the relationship between geomagnetic activity and the magnetic cloud structure. The proposed study establishes the dependence of the high-latitude geomagnetic activity level on the intensity of turbulent processes occurring at the leading edge of the magnetic field. In turn, turbulent phenomena in magnetic cloud sheath are largely determined by the orientation of the wave shock plane with respect to the IMF absorbed by the shock wave as it propagates in the solar wind. It is common to distinguish between the terms of a quasi-parallel and quasi-perpendicular shock wave associated with the level of sheath turbulence following the shock wave. Therefore, the proposed metho d of searching for shock waves in the solar wind flux from the spacecraft data is a necessary part of the investigation. The detection and calculation of their shock planes orientation allow us to conclude that the turbulent sheath is also disturbed. In its turn, the disturbance degree of magnetic clouds sheath with the intensity level of the substorm processes is correlated.

Conditions of turbulent motions in sheath clouds and orientation of shock fronts

The intensity of wave motions in magnetic clouds sheath is largely determined by the IMF penetrating into it, in spite of the fact that the energy of the magnetic field in the solar wind is in 1-2 orders of magnitude smaller than the dynamic energy of plasma flow. According to the boundary conditions on the shock wave and the continuity equation $\rho V = const$ behind the shock wave, the plasma velocity drops sharply (in the counting system moving with plasma), and the magnetic field tangential component increases substantially. The magnetic field will suppress the development of plasma wave motions in the cloud sheath when one of the equalities [1] is fulfilled:

$$\left(\frac{\mathbf{B}_1\times\mathbf{V}_1}{V_1V_2}\right)^2 >> 4\pi\rho_2\frac{V_2^{\ 2}}{V_1^2} \text{ or } \left(\frac{\mathbf{B}_1\cdot\mathbf{V}_1}{V_1}\right)^2 >> 4\pi\rho_2 V_2^{\ 2},$$

where V_1 and V_2 are respectively the flow velocities in front of the shock wave and behind it in the counting system moving with the plasma, B_1 – the magnetic field strength before the shock wave. An estimation of the magnetic field energy densities and plasma dynamic energy in the cloud sheath allows us to conclude the presence or absence of turbulent motions.

A necessary condition for the conclusions about the turbulence level in the sheath is establishment of the shock waves presents in the magnetic clouds which is done according to a previously developed method [2]. The orientations of the detected MC shock fronts are determined analogously to [3]. Fig. 1 shows schematically the technique for determining position of the front of the shock wave. In the space of the IMF components (Bx, By, Bz), the vectors $\mathbf{B}_1$, $\mathbf{B}_2$, $\mathbf{B}_3$ and $\mathbf{B}_4$ indicate the total magnetic field vectors at four time t_1, t_2, t_3 and t_4. Since minute data are used, the situation in Fig. 1 describes a four-minute interval. In this case, $\mathbf{B}_2$ and $\mathbf{B}_3$ correspond to the vectors before and after the plane of the shock front. According to the conditions on the front of the MHD shock wave, the IMF normal component to the shock wave front surface is unchanged, so the vector $\mathbf{\Delta B}_{23}$, which shows the change in the IMF value, lies in the plane of the front of the shock wave. The maximum value of this vector is one of the signs of front of the shock wave registration, along with jumps of plasma flow density and the velocity. Based on these considerations, we determine the position of the discontinuity.

The orientation of the shock wave front associated with the cloud from one-dimensional measurements of the IMF and solar wind parameters before and after the shock wave with the help of IMF co-planarity theorem [4] can be established, according to which the normal to the shock wave is parallel to the vector product

$$\mathbf{N} = \Delta\mathbf{B}_{23} \times (\mathbf{B}_2 \times \mathbf{B}_3),$$

where $\mathbf{B}_2$ is the magnetic field ahead of the shock wave, $\mathbf{B}_3$ is the magnetic field behind it, $\Delta\boldsymbol{B}_{23} = \boldsymbol{B}_3 - \boldsymbol{B}_2$. Thus, the vector $\Delta\mathbf{B}_{23}$ is perpendicular to the vector which is normal to the shock wave plane. It is indicated in Fig. 1 by an arrow with index **n** parallel **N**. For the conclusions about the quasiparallelity or quasi-perpendicularity of the shock waves for considered events, we will be interested in the angle values between the vectors $\mathbf{B}_2$ and **n**, which easily computed on the basis of the scalar product of these vectors.

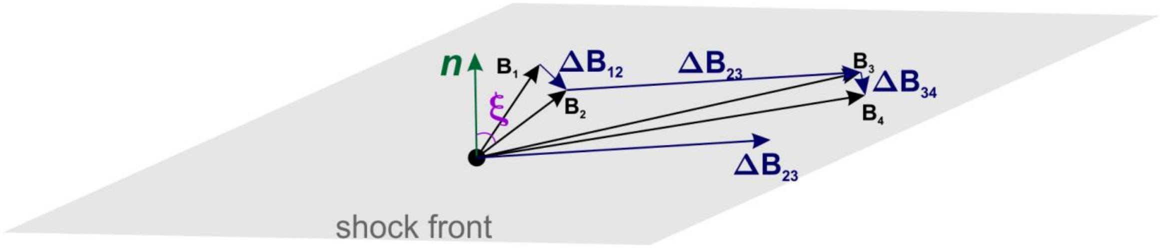

Figure 1. Determination of the shock front position in the space of IMF components (Bx, By, Bz) values. ξ - the angle between the normal to the shock wave plane and the IMF vector having the vectors $\mathbf{B}_2$ and $\mathbf{B}_3$ before and after the break, respectively

If we know the position of the shock front and trace the change in the angle between the IMF vector $\mathbf{B}_2$ and the normal **n** to the shock wave in the data stream, we can conclude that the shock wave is quasiparallel ($\xi \leq 30°$) or quasi-perpendicular ($\xi \geq 60°$) and associate its orientation with the magnetic activity in the auroral zone.

Comparison of turbulence levels in the magnetic clouds sheath with substorm activity level

The procedure verification was carried out by using data which correspond to the observations intervals of fast magnetic clouds with shock waves and a turbulent region - total of 33 cases registered in 1998-2012. The following parameters were used for the study with a 1-min resolution: the concentration N, the solar wind velocity V and the IMF vector B components (Bx, By, Bz) in the GSM coordinate system and polar electrojet index AL values characterizing the substorm magnetic activity level (*http://cdaweb.gsfc.nasa.gov*). Separately examined are the most intensive (13/06/1998, 19/10/1998, 06/11/2000) and weak (21/04/2001, 30/09/2001, 19/11/2007) substorm expressions. The substorm activity by the integral value of the AL index for the period from the moment of shock wave detection to the MC body beginning was estimated, on the interval corresponding to the transition region.

The analysis of obtained calculations showed that the events of quasi- perpendicular shock waves are characterized by angles ξ from interval 70-80^0, events of quasi-parallel shock waves show small angles ξ on average 25^0. Large angles for quasi- perpendicular shock waves with a constant magnetic field normal component lead to a significant increase in the IMF module in the transition region, which, according to [1], should stabilize turbulent motions inside. Fig. 2 shows variation of the angles ξ between the IMF vector and the normal to the shock wave before and after recording the shock front for considered events: (a, b, c) - events with weak substorm activity; (d, e, f) - with strong substorm activity. The vertical line in the center shows the moment of shock front registration. The markers are the analyzed points corresponding to the angles ξ just before the front of the shock wave. The event date in the upper right corner of each chart is indicated. The cases of registering angles greater than 90° correspond to the situation of reversal of the calculated plane of the shock front.

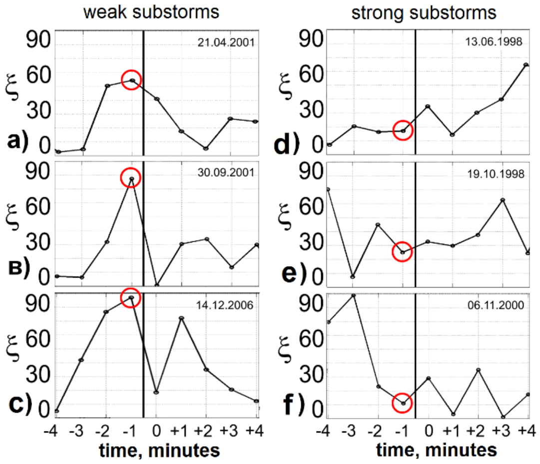

Figure 2. Variation examples of angles ξ between IMF vector and the normal to the shock wave before and after recording the shock wave front: (***a***, ***b***, ***c***) are events with weak substorm activity; (***d***, ***e***, ***f***) - with strong substorm activity. The vertical line in the center shows the moment of shock front registration. The markers identified the analyzed points corresponding to angles just before the shock wave front. The event date is indicated in the upper right corner of each chart.

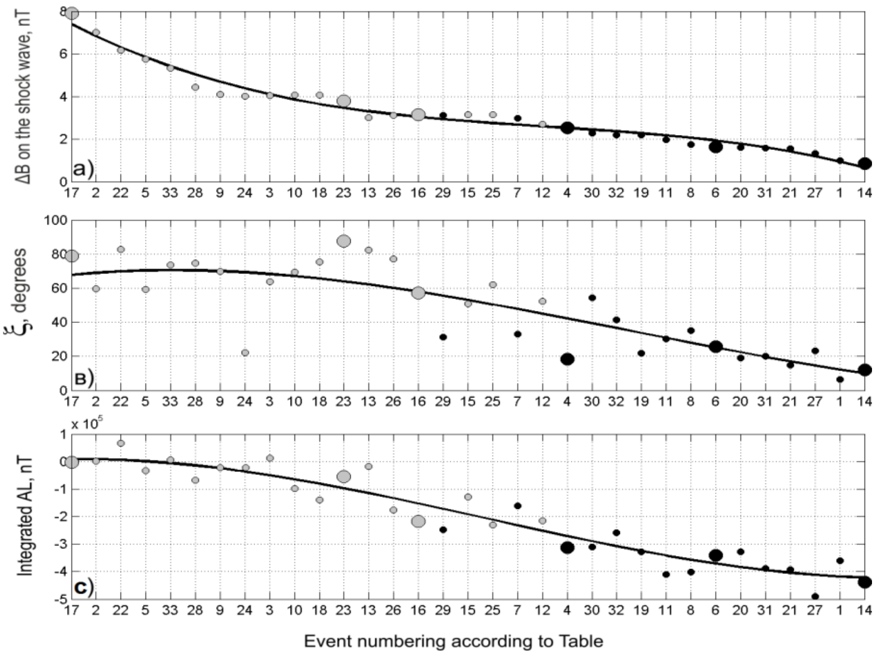

Figure 3. Dynamics of angles ξ between the IMF vector and the normal to the shock front (***a***); the magnitude of the IMF jumps on the shock wave (***b***); the values of the integral AL (***c***). *Gray points* are quasi-perpendicular shock wave, *black points* are quasiparallel shock wave (large circles correspond to the events in Fig. 2), *solid lines* are approximations by a polynomial of order 3 for all analyzed 33 cases of MC. The events distribution is performed taking into account the sorting by values of the IMF jumps on shock waves.

Table. Analyzed events of fast MC registration (bold marked reference points on Fig. 3)

No	**date**	**No**	**date**	**No**	**date**
1	06.01.1998	12	03.10.2000	**23**	**14.12.2006**
2	04.03.1998	13	28.10.2000	24	19.11.2007
3	01.05.1998	**14**	**06.11.2000**	25	05.04.2010
4	**13.06.1998**	15	19.03.2001	26	28.05.2010
5	24.09.1998	**16**	**21.04.2001**	27	03.08.2010
6	**19.10.1998**	**17**	**30.09.2001**	28	14.02.2011
7	18.02.1999	18	18.03.2002	29	30.03.2011
8	16.04.1999	19	17.04.2002	30	05.06.2011
9	20.02.2000	20	20.03.2003	31	25.10.2011
10	15.07.2000	21	14.06.2005	32	22.01.2012
11	10.08.2000	22	13.04.2006	33	23.04.2012

The obtained results are supported by analysis of dynamics of the angles ξ between the IMF vector and the normal to the shock wave front, the magnitude of IMF ΔB modulus jumps on shock wave, and the values of the integral index AL. Fig. 3 show this dynamics. Large angles ξ for quasiperpendicular shock waves with a constant magnetic field normal component lead to an appreciable jump in the IMF. On the contrary, small angles ξ for quasiparallel cases cause small changes in the IMF modulus. This means that large values of the magnetic field modulus ΔB behind the shock wave stabilize the wave processes in the transition region and reduce the intensity level of turbulent motions [1]. According to Fig. 3, these values correspond to the lowest substorm activity. In Fig. 3 shows the dynamics of the angles ξ between the IMF vector and the normal to the shock front (a); the magnitude of the IMF jumps on the shock wave (b); the values of integral index AL (c). The gray points are marked quasi-perpendicular shock waves, the black points are merked quasi-parallel shock waves (large circles correspond to the events in Fig. 2), solid lines are approximations by a polynomial of order 3 for all analytic 33 cases of MO. The events distribution is performed taking into account the sorting of the values of the jumps of the IMF on shock waves.

Conclusion

In this paper is demonstrated the increase of substorm processes intensity in cases of quasi-parallel shock waves of solar wind magnetic clouds. This means that our understanding of the relationship between substorm activity and the level of turbulent processes in the sheath following the shock front of magnetic clouds is confirmed experimentally. The intensity of turbulent processes in sheaths is largely determined by the orientation of shock wave fronts relative to the interplanetary magnetic field vector and is particularly large in the case of quasi-parallel shock waves. Thus, the level of substorm activity follows the level of turbulence in the sheath of magnetic clouds and is determined by the orientation of shock wave fronts relative to the IMF.

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References

1. Barkhatov N.A., Bellyustin N.S., Bughere J.-L., Sakharov S.Yu., Tokarev Yu.V. Influence of the magnetic field of the solar wind on the turbulence of the transition region behind the departing shock wave // News of the Universities "Radiophysics". V.44. N. 12. pp. 993-1002. 2001.
2. Barkhatov N.A., Revunov S.E. Neural network classification of discontinuities in parameters of cosmic plasma. Scientific publication: Solar-terrestrial physics. Issue 14 (127). pp. 42-51. 2010.
3. Barkhatov N.A., Dolgova D.S., Revunova E.A. Geomagnetic activity of magnetic clouds structure // Geomagnetism and Aeronomy, V. 58, 2018 (reviewed)
4. Hundhausen A. Expansion of the crown and solar wind. Moscow: Mir, 302 p. 1976.