EVOLUTION OF GEOEFFECTIVE DISTURBANCES IN INTERPLANETARY SPACE

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ABSTRACT

There are three main sources of geoeffective negative B_z component of interplanetary magnetic field: a) magnetic field inside coronal mass ejections; b) drapery of quiet, usually directed along the line Sun-Earth interplanetary field around disturbances; c) fast solar wind flows, which can form negative B_z component when compressed in Earth's magnetosheath. Comparative study of these effects showed that a combination of b) and c) can be more geoeffective than magnetic cloud itself. A method used in this work is based on analysis of potential functions of disturbed fields. At first a modification of interplanetary field around super-sonic magnetic cloud is found, and then a field extra compression after Earth's bow shock is calculated.

1. INTRODUCTION

The problem of magnetic field and plasma modification in incoming flow interacting with cylindrical obstacles was studied numerically and analytically by solving of full magnetohydrodynamics (MHD) system of equations assuming that $\rho = const$ outside the body ([1], [2]). We relax this simplification and use another method based on assumption that there are no currents in the region between cloud's surface and a bow shock (current-free magnetohydrodynamics). At first, a disturbed magnetic field was found under the following conditions: (i) there is no normal component on cloud's boundary; (ii) normal component is continuous on the bow shock; and (iii) there is no modification of the field at infinity. This approach is used for study of interplanetary magnetic field (IMF) around Earth's magnetosphere. The idea is that disturbances of IMF caused by propagation of a coronal mass ejection (CME) can form regions with $B = 4B_0$ or stronger in case of super-sonic CME. On the other hand, these disturbances are amplified at the Earth's bow shock with an extra factor $\beta \approx 2$. Theoretically, this mechanism of drapery can produce local increase of magnetic field just outside magnetopause up to $B = 4\beta B_0 \approx 8B_0$, where $B_0 \approx 5nT$ is the magnitude of undisturbed IMF near the Earth's orbit. If the B_z component of the disturbed field is negative and greater than $10 \div 15nT$ for a few hours – strong geomagnetic storms can be triggered. For comparison, values of the field inside magnetic cloud are usually less than $30 \div 35nT$. So proposed mechanism can play important role in formation of geoeffective structures in interplanetary space.

2. FIELD DISTRIBUTION AROUND A SLOW CYLINDRICAL CLOUD.

Let us consider magnetic cloud of cylindrical shape. The cylinder's axis makes the angle α with the X axis, and its projection to the XY plane makes the angle β with the Y axis. Initial undisturbed field is uniform and directed along the X axis. This field is determined by the potential

$$\Psi_0 = B_0 x = B_0 \left(r \cos\varphi \sin\alpha + Z \cos\alpha \right) \qquad (1)$$

Here r, φ, and Z form cylindrical system of the cylinder:

$$\tilde{x} = r \cos\varphi \qquad (2)$$

$$\tilde{y} = r \sin\varphi \qquad (3)$$

$$\tilde{z} = Z \qquad (4)$$

Here

$$\tilde{x} = x \sin\alpha - y \cos\beta \cos\alpha - z \sin\beta \cos\alpha \qquad (5)$$

$$\tilde{y} = y\cos\beta - z\sin\beta \qquad (6)$$

$$\tilde{z} = x\cos\alpha + y\cos\beta\sin\alpha + z\sin\beta\sin\alpha \qquad (7)$$

And the disturbed potential is

$$\Psi_1 = B_0\left(r\left[1 + \frac{r_0^2}{r^2}\right]\cos\varphi\sin\alpha + Z\cos\alpha\right) \qquad (8)$$

The magnetic field components directly follow from Eq. 8:

$$B_x = B_0 + \frac{r_0^2}{r^4}\Big\{\left(y\cos\beta - z\sin\beta\right)^2 - \\ -\left(y\cos\beta\cos\alpha + z\sin\beta\cos\alpha - x\sin\alpha\right)^2\Big\} \qquad (9)$$

$$B_y = B_0\Big\{\left(y\cos\beta\cos\alpha + z\sin\beta\cos\alpha - x\sin\alpha\right)\times \\ \times\Big(y\cos^2\beta\left\langle 1 + \cos^2\alpha\right\rangle + z\sin\beta\cos\beta\left\langle\cos^2\alpha - 1\right\rangle - \\ -x\cos\beta\sin\alpha\cos\alpha\Big) - \left(y\cos\beta - z\sin\beta\right)\times \\ \times\left(-2z\sin\beta\cos\beta\cos\alpha + x\sin\alpha\cos\beta\right)\Big\}\frac{r_0^2}{r^4}\sin\alpha \qquad (10)$$

$$B_z = B_0\Big\{\left(y\cos\beta\cos\alpha + z\sin\beta\cos\alpha - x\sin\alpha\right)\times \\ \times\Big(y\cos\beta\sin\beta\left\langle\cos^2\alpha - 1\right\rangle + z\sin^2\beta\left\langle\cos^2\alpha + 1\right\rangle - \\ -x\sin\beta\sin\alpha\cos\alpha\Big) - \left(y\cos\beta - z\sin\beta\right)\times \\ \times\left(-2y\cos\beta\sin\beta\cos\alpha - x\sin\beta\sin\alpha\right)\Big\}\frac{r_0^2}{r^4}\sin\alpha \qquad (11)$$

In Eqs. 9-11 $r = \sqrt{\tilde{x}^2 + \tilde{y}^2}$. These equations describe the magnetic field outside the cloud, $r > r_0$. It follows from these equations that the maximum field increase is 2 times in comparison with undisturbed values. For super-sonic clouds this increase is 2ε times ([3]), $\varepsilon = \frac{r_1}{r_1 - r_0}$, r_1 is the distance from the cloud's center to bow shock. A similar analysis for a toroidal cloud has been done in [4]. On Fig. 1 and 2 field lines and magnitude distribution are shown for the case of super-sonic cylindrical cloud.

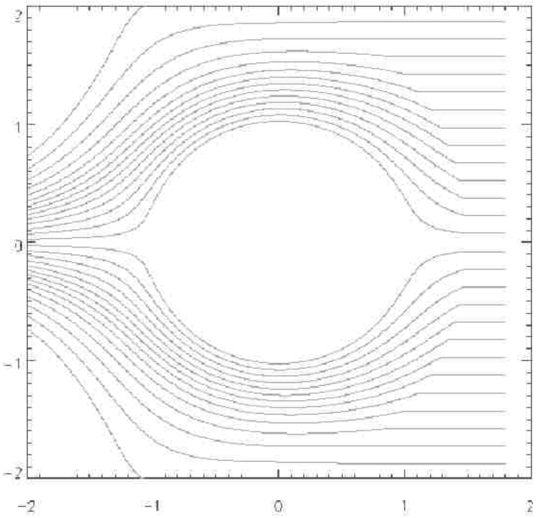

Fig.1. Magnetic field lines around super-sonic magnetic cloud.

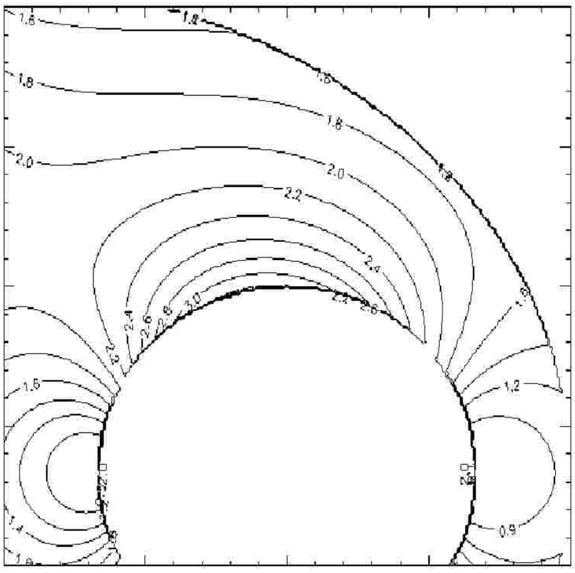

Fig.2. Contours of field magnitude around super-sonic magnetic cloud.

3. MODIFICATION OF IMF NEAR EARTH'S MAGNETOPAUSE

A uniform field directed along the X axis of solar ecliptic co-ordinates is modified by paraboloid of rotation in the way determined by the following formulas:

$$\tilde{B}_x = \tilde{B}_0\left(\frac{x_0}{l} - 1\right) \tag{12}$$

$$\tilde{B}_y = -\tilde{B}_0\left(\frac{x_0 y}{l^2 - xl}\right) \tag{13}$$

$$\tilde{B}_z = -\tilde{B}_0\left(\frac{x_0 z}{l^2 - xl}\right) \tag{14}$$

In these formulas $l = \sqrt{x^2 + y^2 + z^2}$ and x_0 is the distance to sub-solar point of magnetopause from the Earth's centre. $\tilde{B}_0$ in Eqs. 12-14 is the field's magnitude in incoming solar wind and for disturbed case can be estimated by using formulas obtained in Section 2: $\tilde{B}_0 \approx 2\varepsilon B_0$ for sub-sonic conditions on magnetopause is of the order of $4B_0$.

Because there is a super-sonic flow around the Earth's magnetosphere, Eqs. 12-14 are modified by multiplication of $\tilde{B}_0$ by an extra factor $\chi = \frac{x_1}{x_1 - x_0}$, where x_1 is the distance to the Earth's bow shock. Assuming $\chi = 2$ in a general case one can see $\tilde{B}_0 \approx 4 \cdot 2B_0 \approx 8B_0$. The magnetic field just outside the magnetopause can be 8 times stronger than that of quiet IMF due to the action of drapery around a CME and the Earth's magnetosphere. On Fig. 3 and 4 magnitude distribution and field lines are shown for the case of IMF drapery around the Erath's magnetosphere.

4. CONCLUSIONS

Magnetic disturbances caused by super-sonic drapery of IMF around CME and the Earth's magnetosphere was solved analytically and used for evaluation of a possible geo-effectiveness of this phenomena.

5. ACKNOWLEDGEMENTS

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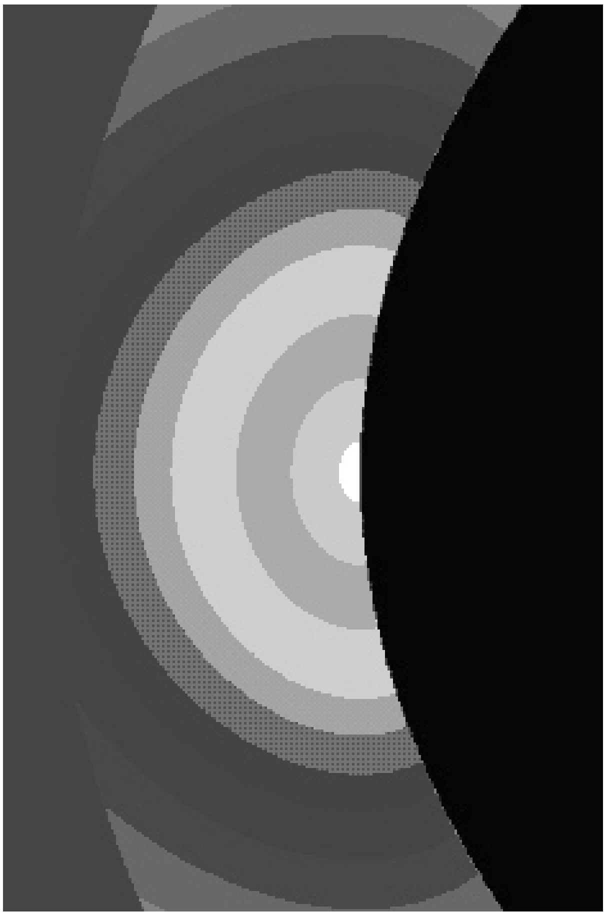

Fig. 3. Magnetic field magnitude contours for the region between a bow shock and magnetopause

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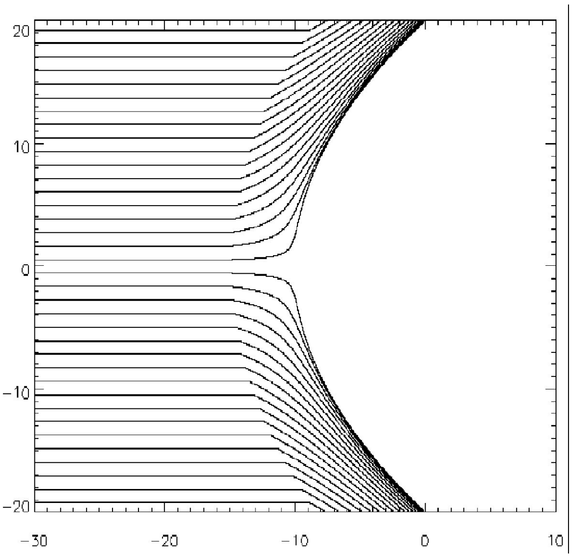

Fig. 4. The field lines around magnetopause for the case of super-sonic solar wind with IMF directed along the X axis.