Interaction Of Magnetic Clouds In The Inner Heliosphere

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Abstract. A method of potentials has been used in the past for the calculation of the force acting on isolated magnetic bodies in solar corona and inner heliosphere, where large gradients of magnetic pressure exist. Since recent observations showed that coronal mass ejections (CME) can leave the Sun more frequently than was expected before 1995, it is clear that interactions between CMEs can play important role in the formation of geo-effective structures near the Earth’s orbit. We present here an evaluation of two interacting CMEs and the field distribution around them, using potential solution in bi-cylindrical coordinates.

INTRODUCTION

In attempts to find the value of a force acting on an isolated body in solar corona, Parker [1] proposed a potential magnetic field, and found an expression for the force: the so called “melon seed mechanism”. The magnetic structure inside the cloud was assumed to be force-free [2]. Later another form of this distribution in cylindrical geometry [3] was used in the literature for interpretation of magnetic clouds observations. Romashets and Vandas [4] used the method for the study of more complicated, toroidal-shape clouds dynamics in solar wind. There were many studies of non-potential flow around such kinds of cylindrical and spherical bodies [5-7] using an MHD approach, both analytically and numerically. But no explicit expression for field and force were found.

CALCULATION: POTENTIAL FIELD

Assume two cylinders aligned along the Z axis are inserted into initially uniform X-directed field. The cloud magnetic fields have no connection with the ambient field. In bi-cylindrical coordinates the initial field potential is

\[ \Psi_0 = B_0 \cdot x = B_0 \cdot a \sum e_n e_r \cdot \cos n\eta \]  \hspace{1cm} (1)

Here \( a \) is a parameter of the coordinate system, \( e_n = 1 \) for \( n = 1 \), \( e_n = 2 \) for \( n \geq 2 \). The following relations hold between cartesian coordinates and new coordinates \( \mu, \eta \) and \( Z \):

\[ x = \frac{a \sinh \mu}{\cosh \mu - \cos \eta}, \hspace{1cm} (2) \]

\[ y = \frac{a \sin \eta}{\cosh \mu - \cos \eta}, \hspace{1cm} (3) \]

\[ z = Z, \hspace{1cm} (4) \]

and the radii of cylinders are equal to

\[ r_0 = \frac{a}{\sinh \mu_0}, \]  \hspace{1cm} (5)

the distance between their centers is:

\[ D = 2 r_0 \cosh \mu_0 = 2acth \mu_0. \]  \hspace{1cm} (6)

The equation \( \mu = [\mu_0] \) defines the cylinder’s surfaces in new coordinates. On insertion of the two clouds, the ambient field has been changed and distorted in such a way that

\[ \left. B_0 \right|_{\mu_0=\mu} = 0 \]  \hspace{1cm} (7)
The new potential is then
\[ \Psi = B_e a \sum_{n=0}^{\infty} \varepsilon_n (e^{-in} + e^{in}) \cos n \eta \]  
(6)
chosen among harmonic functions satisfying (5) and asymptotic to equ. (1) at infinity.

THE DISTURBED FIELD
The components of the disturbed field are:
\[ B_x = 2 B_e \left\{ (1 - \cosh \mu \cos \eta) \sum_{n=0}^{\infty} n (e^{-2in} - e^{-in}) \cos n \eta + \right. \\
\left. + \sinh \mu \sin \eta \sum_{n=0}^{\infty} n (e^{-2in} + e^{-in}) \sin n \eta \right\} \]  
(7)
\[ B_y = 2 B_e \left\{ - \sinh \mu \sin \eta \sum_{n=0}^{\infty} n (e^{-2in} - e^{-in}) \cos n \eta + \right. \\
\left. + (\cosh \mu \cos n \eta - 1) \sum_{n=0}^{\infty} n (e^{-2in} + e^{-in}) \sin n \eta \right\} \]  
(8)
where
\[ \mu = \frac{1}{2} \ln \frac{(x+a)^2 + y^2}{(x-a)^2 + y^2} \],  
(9)
\[ \eta = \frac{i}{2} \ln \frac{(y-ia)^2 + x^2}{(y+ia)^2 + x^2} \].  
(10)

THE FORCE ON THE FLUX ROPES
AND EXAMPLE
The force acting on each cylinder is
\[ F_x = \int_{S} B_e \cdot dS = - \frac{2B_e^2}{\pi a} aL \cdot \int_{\eta} \left( \cosh \mu \cos \eta - 1 \right) \sum_{n=0}^{\infty} n e^{-n \mu \cos n \eta} d\eta \]  
(11)
and is directed along X axis. This force moves the CMEs closer to each other. The following example can describe the situation near the Earth’s orbit more adequately. The initial external field is
\[ B_x = B_0 + \frac{B_1 x}{a} \]  
(12)
\[ B_y = - B_0 - \frac{B_1 y}{a} \]  
(13)
where \( B_0 \) is the averaged value of x-component near the location being considered, for example near the 1 AU. \( \frac{B_1}{a} \) measures the gradient of each component. In this case the disturbed potential is:
\[ \Psi = B_e a \sum_{n=0}^{\infty} \varepsilon_n (e^{-in} + e^{in}) \cos n \eta - \]  
\[ - B_e a \sum_{n=0}^{\infty} 2 (e^{-in} + e^{in}) \sin n \eta + \]  
\[ + B_e a \sum_{n=0}^{\infty} n (e^{-in} + e^{in}) \cos n \eta \]  
(14)
In Figure 1 one can see contours of magnetic field magnitude.

FIGURE 1. Sample contours of magnetic field magnitude disturbed by insertion of two cylindrical magnetic clouds into medium with initially non-uniform field.
The force acting on each of two cylinders has the following components:

\[ F_x = -\frac{2aL}{\pi} \int_{-\pi}^{\pi} (\cosh \mu \cos \eta - 1) (B_\rho(\mu_0, \eta))^2 d\eta \]  
\[ F_y = -\frac{2aL}{\pi} \int_{-\pi}^{\pi} \sinh \mu \sin \eta (B_\rho(\mu_0, \eta))^2 d\eta \]  

(15)

(16)

If the equations of motions are solved for both cylinders using (15) and (16), it will be seen that two bodies are rotating with respect to each other. There is only a stable orientation for \( \varphi = 45^0 \).

For evaluation of (15) and (16), we can use an approximation of interplanetary magnetic field (IMF):

\[ B_r = B_e \frac{r^2}{r_e^2} r_e^2, \quad B_\varphi = B_e \frac{r_e}{r^2} r_e \]  

(17)

where \( B_e = 3 \text{nT} \) is the averaged value of IMF components at 1 AU, \( r_e = 1 \text{AU} \), \( r \) is the distance from the center of the Sun. Now we can find gradient of magnetic field:

\[ \frac{\partial B_r}{\partial r} = -\frac{2B_e}{r^3} r_e^2 \]  

(18)

\[ \frac{\partial B_\varphi}{\partial r} = \frac{B_e}{r^2} r_e \]  

(19)

From (12), (13) and (18), (19) it can be seen that we can take \( B_0 = B_e \) and \( B_1 = -\frac{3B_e a}{2r_e} \) for conditions at 1 AU. Using these values in (14) we have:

\[ B_r(\mu, \eta) = 2B_e \sum \frac{\sin \eta}{\eta} \left( \frac{2 + 3na}{2r_e} \right) \cosh(\eta - \mu_0) \cos\left(\eta + \frac{\pi}{4}\right) = 2B_e e^{\mu_0} \left( \frac{2 + 3na}{2r_e} \right) \cosh(\mu - \mu_0) \cos\left(\eta + \frac{\pi}{4}\right) \]  

(20)

and from (15), (16) we have the force:

\[ F_x = 32aL B_e e^{\mu_0} \left( 1 + \frac{3a}{2r_e} \right) \]  

(21)

CONCLUSIONS

Modification of the IMF around two cylindrical CMEs was found using a potential field formulation in bi-cylindrical coordinates. The results can be used for a calculation of the force acting on both CMEs during their motion from the Sun. Plasma parameters distribution for this geometry were not found but can be if the entire system of MHD equations is solved for V, n, and T and will be the subject of future work. The maximum increase of B around both clouds is a factor of 2-3, and one can expect that the velocity will increase by a similar amount. Streamlines can be slightly different from field lines but resemble them in general.

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REFERENCES