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Journal of Atmospheric and Solar-Terrestrial Physics 70 (2008) 593–597

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Solar corona expansion and heliospheric current sheet creation

I.M. Podgorny[a,*], A.I. Podgorny[b]

[a]Institute for Astronomy RAS, Moscow 119017, Russia
[b]Lebedev Physical Institute RAS, Leninsky Prospect, 53, Moscow 119991, Russia

Accepted 27 August 2007
Available online 6 October 2007

Abstract

Heliospheric current sheet (CS) creation has been investigated by numerical solution of 3D MHD equations, using the PERESVET code to the problem of solar corona expansion. The dipole magnetic field corresponds to the solar activity minimum, and typical corona parameters are used as initial conditions. Plasma compression, dissipation, thermal conductivity, and gravitation are taken into account. The normal magnetic field component is an important feature of the heliospheric CS. The sheet cannot be a neutral one. Current generation is similar to action of a short closed MHD generator. The solar wind temperature is determined by plasma cooling because of plasma expansion and heat conduction from the Sun. In the process of expansion the solar wind is accelerated and achieves the supersonic velocity at a distance of about 3 solar radii. The CS is surrounded by a thick plasma sheet. Plasma velocity is decreased inside the sheet as demonstrated by previous workers.

Keywords: Solar wind; Current sheet; Solar corona; MHD

1. Introduction

Corona thermal expansion takes place in presence of gravitation and solar magnetic field. It is possible to select an integration constant in the motion equation so that the acceleration works continuously (Parker, 1963), and the supersonic velocity is achieved at some critical distance from the Sun. This result has been obtained in isothermal approximation, the anisotropy of heat conductivity in the magnetic field is not taken into account. It is difficult to excuse the isothermal condition, because the corona temperature is ~200 eV, and the solar wind temperature at the Earth orbit is ~20 eV. These restrictions are absent in the numerical experiment presented here.

The solar corona expansion produces supersonic plasma flow (solar wind) and Sun magnetic field line stretching. The magnetic field configuration is mostly determined by the current in the closed heliospheric current sheet (CS) located near the ecliptic plane. The possible magnetic field configuration has been the first time considered in 2D steady state approximation (Pneuman and Kopp, 1971). The gravitation was neglected, and necessity of a neutral line was assumed. This assumption is difficult to justify. Pneuman and Kopp (1971) claim absence of a normal magnetic component B_n in the CS and existence of two classes of magnetic field lines (closed and opened). These conclusions,

*Corresponding author.
E-mail address: podgorny@inasan.ru (I.M. Podgorny).

1364-6826/$ - see front matter
doi:10.1016/j.jastp.2007.08.048

accordingly, are very doubtful. The mistaken conclusion about absence of B_n in the heliospheric CS is obvious. There are no possibilities to generate a current in a stationary neutral ring CS. For current generation it is necessary to have conductive liquid flow across the magnetic field. Ohm's Law in MHD approximation is $\mathbf{j}/\sigma = \mathbf{E} + \mathbf{V} \times \mathbf{B}/c$. The polarization electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}/c$ appears only during restricted conductor motion across the magnetic field because of $\mathbf{j} = 0$. As a result, the electric charges of opposed polarity are induced at the conductor edges. In the ring current at radial expansion of the solar corona the charges move freely under Lorenz force action, and polarization does not appear. In the steady state there is no electric field induced by $\partial \mathbf{B}/\partial t$. The current density becomes as $\mathbf{j} = \sigma \mathbf{V} \times \mathbf{B}/c$. There are no other possibilities for a stationary ring current generation. The ring CS appears only in the presence of a normal magnetic field component B_n. The current value in such a generator is determined by its internal resistance. Existence of B_n means that magnetic lines cannot be divided in closed and opened, as has been proclaimed in Pneuman and Kopp (1971). All field lines that come out of one solar hemisphere enter the other one crossing the ring CS.

The results of numerical MHD calculations for stationary solar wind (Usmanov, 1993) carried out with typical simplifications contradict the assumption by Pneuman and Kopp (1971) and more recent workers. They show existence of a normal magnetic component in the heliospheric CS. The 2D MHD simulation of plasma blobs due to reconnection (Wu et al., 2000) represents a special case. In our recent 3D MHD calculations the thermal expansion of the corona has been demonstrated (Podgorny et al., 2004). Here we present some data concerning supersonic solar wind creation and the main characteristic of the heliospheric CS, including normal magnetic field component. The modern PERESVET code was used (Podgorny and Podgorny, 2004).

2. Equations

The system of resistive 3D MHD equations for compressible plasma is solved using PERESVET code. Dimensionless 3D MHD equations have a form

$$\frac{\partial \mathbf{B}}{\partial t} = \operatorname{rot}(\mathbf{V} \times \mathbf{B}) - \frac{1}{Re_m} \operatorname{rot}\left(\frac{\sigma_0}{\sigma} \operatorname{rot} \mathbf{B}\right), \tag{1}$$

$$\frac{\partial \rho}{\partial t} = -\operatorname{div}(\mathbf{V}\rho), \tag{2}$$

$$\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V}, \nabla)\mathbf{V} - \frac{\beta_0}{2\rho}\nabla(\rho T) - \frac{1}{\rho}(\mathbf{B} \times \operatorname{rot} \mathbf{B}) + \frac{1}{Re\rho}\Delta \mathbf{V} + G_g \mathbf{G}, \tag{3}$$

$$\begin{aligned}\frac{\partial T}{\partial t} = &-(\mathbf{V}, \nabla)T - (\gamma - 1)T \operatorname{div} \mathbf{V} \\ &+ (\gamma - 1)\frac{2\sigma_0}{Re_m \sigma \beta_0 \rho}(\operatorname{rot} \mathbf{B})^2 \\ &- (\gamma - 1)G_q L'(T)\rho \\ &+ \frac{\gamma - 1}{\rho}\operatorname{div}[\mathbf{e}_\parallel \kappa_{dl}(\mathbf{e}_\parallel, \nabla T) \\ &+ \mathbf{e}_{\perp 1}\kappa_{\perp dl}(\mathbf{e}_{\perp 1}, \nabla T) + \mathbf{e}_{\perp 2}\kappa_{\perp dl}(\mathbf{e}_{\perp 2}, \nabla T)].\end{aligned} \tag{4}$$

Here, $Re_m = L_0 V_0 / \nu_{m0}$ is the magnetic Reynolds number, $\nu_{m0} = c^2/4\pi\sigma_0$ is the magnetic viscosity for the conductivity σ_0 at the temperature T_0, σ is the conductivity, $\sigma_0/\sigma = T^{-3/2}$, $\beta_0 = 8\pi n_0 k T_0 / B_0^2$, ($n_0 = \rho_0/m_i$, m_i is the ion mass). $Re = \rho_0 L_0 V_0/\eta$ is the Reynolds number, η is the viscosity. $G_q L'(T)$ is the dimensionless radiation function. $\mathbf{e}_\parallel, \mathbf{e}_{\perp 1}, \mathbf{e}_{\perp 2}$ are the orthogonal unit vectors that are correspondingly parallel and perpendicular to the magnetic field. $G_g \mathbf{G}$ is the dimensionless gravitational acceleration. $L_0 = 8R_\odot$ is the dimensionless length.

Representative calculation parameters are: $\gamma = \frac{5}{3}$, $Re_m = 8 \times 10^4$, $Re = 10^4$, $\beta_0 = 8 \times 10^{-6}$. The Peclet numbers along and across the magnetic field are $\Pi = 2$ and $\Pi_B = 2 \times 10^6$. The idea of choosing dimensionless parameters is presented in Podgorny and Podgorny (1996). The numerical Reynolds number at the net of $41 \times 41 \times 41$ is $\sim$50.

3. Numerical methods

The methods used for solving the system of resistive 3D MHD equations for compressible plasma are described in Podgorny et al. (2004). Solar gravitation and anisotropy of the thermal conductivity are taken into account. Implicit scheme, that is conservative relative to the magnetic flux, permits avoidance of errors connected with numerical $\operatorname{div} B$ approximation. The calculations are carried out in the box $8R_\odot \times 8R_\odot \times 8R_\odot$ with the net $41 \times 41 \times 41$. The scheme of calculation in the plane $Y = 4R_\odot$ is shown in Fig. 1a. The constant coronal plasma parameters (the temperature $T = 220\,\mathrm{eV}$, the density $n = 2 \times 10^7\,\mathrm{cm}^{-3}$, and