Numerical MHD Simulation of Flux-Rope Formed Ejecta Interaction With Bimodal Solar Wind

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Abstract. A theoretic numerical simulation of interaction between CME ejecta and bimodal solar wind from solar surface to 30 solar radii has been presented. A comparison with an interaction between CME ejecta with homogeneous and bimodal solar wind is given. The results show that the bimodal solar wind changes the topology of CME ejecta with faster propagation speed away from the equator, and fast wind will energize the CME. Also the results of steady-state bimodal solar wind characteristics that extend to 1AU are presented.

INTRODUCTION

Observation, especially Ulysses, showed that the solar wind consists of both fast and slow components in the solar minimum [1,2]. In this bimodal characteristics of solar wind there are an almost homogeneous high-speed flow over coronal hole and the low-speed flow over coronal streamer with the division between them at about 70° from the pole. The bimodal solar wind property is very important to study the propagation of Coronal Mass Ejection (CME) which is major large scale solar eruption. The fast solar wind at the coronal hole will affect the propagation speed and the topology of CME.

We combined our bimodal solar wind model [3] and the flux-rope model [4] to investigate the interaction between CME and bimodal solar wind. The purpose of this study is to reveal the physical mechanism that causes the changes of the speed and topology of the CME during the propagation. CMEs are also the major disturb to the Earth environment. In order to study the disturbed solar wind parameters at 1AU due to the CME propagation in a bimodal solar wind environment, we have build a steady-state bimodal solar wind model to present here. Their effects due to propagation of CME will be given elsewhere [5].

MHD MODELS AND RESULTS

In our simple solar wind model we assume an axisymmetric, time-dependent, MHD flow of a single-fluid, polytropic, and fully ionized plasma. In order to obtain bimodal solar wind model, we added volumetric heating, momentum addition, and thermal conduction. The flow is calculated in a meridional plane defined by the axis of the magnetic field. The detailed description of the governing equations can be found in [3].

In simple solar wind model the polytropic index \( \gamma = 1.05 \). Temperature and density at lower boundary (solar surface) are uniform from equator to pole. The plasma \( \beta = 1.0 \) at equator and 0.2 at pole. In bimodal solar wind model the polytropic index \( \gamma = 5/3 \). The temperature and density are not uniform from equator to pole. The plasma \( \beta = 1.0 \) at equator and 0.02 at pole. The volumetric heat source is given by

\[
Q = Q_0 \frac{\rho}{\rho_0} e^{-\frac{(r-R_s)}{L_R_s}} \tag{1}
\]

where \( Q_0 \) is 5x 10^{-8} erg cm^{-3} s^{-1} and \( \rho_0 \) is the base density. A heating term similar to this was used by Hartle and Barnes [6]. The thermal conductive fluxes for a Lorentz gas is given by

\[
q = \kappa |T|^{5/2} (\nabla \cdot T) \frac{\vec{B}}{B^2} \tag{2}
\]

where \( \kappa \) is the collisional thermal conductivity along the magnetic field lines as given by Spitzer [7]. The momentum addition is given by

\[
D = \frac{D_0 a^2}{(r-a)^2 + a^2} \left[ 1 - \arctan\left(\frac{\theta}{\Delta \theta - 14.5}\right)/4 \right] \tag{3}
\]
where $D_0$ with the value of $5 \times 10^3$ dyn/g, $D$ reaches its maximum value at $\alpha$, and $\theta$ is latitudinal angle.

The computational domain is in meridional plane from the pole to the equator in the $\theta$ direction and from the solar surface to 30Rs for the interaction of flux rope and solar wind and to 1AU for quasi-steady state Sun-Earth bimodal solar wind in the radial direction, respectively.

The symmetric boundary conditions are used at two side boundaries. The lower boundary is a physical boundary and the non-reflected characteristic boundary conditions are used. The upper boundary is a computational boundary, and since the flow at this boundary is supersonic and super-Alfvenic the linear extrapolation is used. The detailed description of the boundary conditions are given by [4].

Fig. 1 shows the distributions of the magnetic field, density and velocity of the initial steady state for the simulation of the interaction with a simple and a bimodal solar wind, respectively. The contrast of the density and velocity from the pole to the equator is larger in the bimodal solar wind than that in the simple solar wind. Also the current sheet is thinner in the bimodal solar wind than in the simple solar wind.

CME-SOLAR WIND INTERACTION

To show CME and solar wind interaction a flux-rope emerged from the solar surface centered at the equator. The flux rope’s radius is 0.5Rs. The center thermal pressure is 50 times larger than its edge. The plasma beta at the edge is 0.1 and its emerging speed from the solar surface is 50 km/s. Fig. 2 shows the simulation results at 12 hours. In this figure the evolutionary magnetic field lines, velocity and the density enhancement for both cases, i.e. simple solar wind and bimodal solar wind, are depicted. From this figure the large distortion of the flux rope after interacting with fast speed flow in the bimodal solar wind at open field line region could be seen. The side edges of the flux rope move faster than its center because the fast speed solar wind in open field region which carries the edge of the flux rope with them.
Further, Fig. 3 show the distance-time curve for the edge of the flux-rope. It is clearly indicated that the solar wind has energized the propagation of the flux-rope. As expected this effect will modify the CME induced shock strength which related to particle acceleration.

BIMODAL SOLAR WIND FROM SOLAR SURFACE TO 1AU

To extent the steady-state bimodal solar wind to 1AU we have to choose the following parameters of $a$ and $D_0$ in momentum addition of equation (3). These two parameters are not constants and are function of latitude. The specific equations for them are given as follows:

$$a(\theta) = a_0 - 0.36 \arctan(5(\frac{\theta}{\Delta \theta} - 14.5))$$

(4)

and

$$D_0(\theta) = D'_0 (1 - \arctan(5(\frac{\theta}{\Delta \theta} - 14.5))/3.5$$

(5)

where $D'_0$ has the same value of $D_0$ in the equation (3).

The heating length $L$ in equation (1) is redefined as follows:

$$L = 10 \quad r \leq 20R_s$$

$$L = 12.5 \quad r > 20R_s$$
Some steady-state results are shown in Fig. 4 and Fig. 5.

![Quasi-Steady State Sun-Earth Structure](image)

**FIGURE 4.** Densities and velocities vs heliocentric distance at the pole and the equator are showed.

![Density & Velocity at 1AU](image)

**FIGURE 5.** Densities and velocities vs latitude at 1AU are showed.

By examining Figs. 4 and 5, the solar wind characteristics of this study are: at the solar surface \( n \) (at equator) = \( 10^8 / \text{cm}^3 \) and \( n \) (at pole) = \( 2 \times 10^7 / \text{cm}^3 \); \( v_r \) (at equator) \( \cong 0 \) and \( v_r \) (at pole) = 25 km/s. At 1AU, \( n \) (at equator) = 73/cm³ and \( n \) (at pole) = 12/cm³; \( v_r \) (at equator) = 420 km/s and \( v_r \) (at pole) = 790 km/s. Comparing with the average observational data the number density at equator and pole in our bimodal solar wind model are 2-3 times higher, but the velocity is matched well.

**SUMMARIES AND CONCLUSIONS**

Theoretic numerical simulations for interaction of CME with simple solar wind or bimodal solar wind have been presented up to inner heliosphere in this study. Also the steady-state bimodal solar wind results are showed up to 1AU. The purpose is to lay the ground to study the disturbed solar wind properties due to the CME propagating to the Earth’s environment. We have the following conclusions:

1. Fast speed solar wind will energize the CME.
2. The shape and speed of the flux rope will change during the propagation because the interaction with bimodal solar wind.
3. The forms of heating and momentum addition functions are important to obtain realistic Sun-Earth bimodal solar wind.

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