Modeling the slow solar wind during the solar minimum

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Abstract. During the solar minimum STEREO observations show that the three-dimensional structure of the solar corona can be described well by a tilted bi-polar magnetic configuration. The slow solar wind is modeled using three-fluid model that includes heavy ions, such as He II and O VI. The model is initialized with dipole magnetic field and spherically symmetric density. The resulting steady state non-potential and non-uniform streamer configuration calculated with this model is compared to STEREO observations of the streamer density structure. SOHO/UVCS observations are used to compare the O VI emission to model results. We discuss the unique properties of the solar wind produced in this configuration.

1 Introduction and Motivation

Observations show that the slow solar wind is associated with the streamer belt during solar minimum, and the magnetic configuration near solar minimum is dominated by a tilted dipole. Past UVCS observations show that the emission structure and abundances of O VI and other heavy ions in streamers are different than the properties of Ly α emission (Kohl et al. 1997; Raymond et al. 1997).

As evident from recent NSO and STEREO 3D reconstruction of electron density, and magnetic field using Potential Field Source Surface Model (PFSS) the streamer higher density region is confined to the central part of the tilted dipole with nearly symmetric structure with respect to the tilt plane (Kramar et al. 2009). Figure 1 shows and observational example that justifies the use of 2.5 MHD with dipole field. Global 3D MHD models of the solar wind can capture the overall configuration of the streamers (Mikić et al. 1999). However, these models can not describe the different properties of the various ions.

Recently, Ofman (2000, 2004a) developed the first three-fluid model of a coronal streamer with O $^{5+}$, and He $^{++}$ ions included self-consistently as a third fluid in addition to electrons and protons using quadrupole initial magnetic field. The model was able to reproduce the main observational properties of the heavy ions. Here we present an extensions of the three-fluid 2.5D model of streamers near solar minimum with heavy ions, initiated with dipole magnetic field appropriate for solar minimum, that evolves into the streamer structure in the quasi-steady state. We find that the model reproduces the properties of the slow solar wind protons and of the heavy ions.
2 Multi-fluid model

We solve the normalized multi-fluid equations for $V \ll c$, with gravity, resistivity, viscosity, and Coulomb friction, neglecting electron inertia, assuming quasi-neutrality. The equations can be found in Ofman (2000, 2004b). In Ofman (2000) the heavy ions were isothermal. In the present study we use more realistic Polytropic model with energy coupling term between the ions (Braginskii 1965) with the following energy equation:

$$\frac{\partial T_k}{\partial t} = - (\gamma_k - 1) T_k \nabla \cdot \vec{v}_k - \vec{v}_k \cdot \nabla T_k + C_{kjl},$$

where $k = e, p, i,$ and $\gamma_k = 1.05$ is the polytropic index. The energy exchange terms between the species in equation (1) are given in Ofman (2004b).

In order to reproduce solar minimum conditions we initialized the 3-fluid model with a dipole field (see Figure 2a). The density was initially uniform in $\theta$, the radial dependence of proton density was given by spherically symmetric Parker’s solar wind solution. The heavy ion abundance was initially a constant fraction of the proton density everywhere (i.e., $0.05$ for $\text{He}^{++}$ and $8 \times 10^{-4}$ for $\text{O}^{5+}$ ions). These values evolved self-consistently as the slow solar wind streamer has formed in the quasi-steady state.

3 Numerical Results

In Figures 2b-3 we show the results of the 3-fluid slow solar wind model. In Figure 2 we show the initial dipole field in our $r - \theta$ coordinates, and the transformation of the initially potential magnetic field to the slow solar wind streamer with the current sheet.
Figure 2. The transformation of (a) dipolar field into (b) streamer obtained with the 3-fluid model is shown. The current-sheet is shown in blue scale.

In Figure 3 we shown the quasi-steady state solution obtained for the slow solar wind streamer with He\(^{++}\) and O\(^{5+}\) ions. The density and velocity structure of the slow solar wind streamer is evident. The regions of highest ion density as a function of \(\theta\) occur at the interface of escaping and confined plasma regions and at the streamer stalk, while the lowest heavy ion density occurs at the central (confined) part of the streamer. The He\(^{++}\) ion density and velocity structure is similar to the O\(^{5+}\) ion structure. The details of the streamer cross-sectional structure at \(r = 1.5R_s\) and at \(r = 5R_s\) for protons and He\(^{++}\) ions is shown in Figure 4. The anti-correlation between the protons and He\(^{++}\) abundance and the relation to the outflow speed is evident. The proton density dependence with height is in qualitative agreement with Figure 1.

Figure 3. The density of the ions in the slow solar wind streamer overlaid with the ions outflow speed.
4 Conclusions

During the solar minimum the solar magnetic field is dominated by a tilted dipole, and the slow solar wind is associated with a single streamer belt, as evident from 3D reconstruction using STEREO/COR1 and NSO/GONG data. SOHO/UVCS observations of Ly-α, O VI, and other minor ion emission lines in streamers provide clues for the acceleration and heating mechanism, and require multi-fluid and kinetic modeling in order to interpret the results.

We find that 3-fluid models of compositional structure of streamers initiated with a dipole field reproduce the observational properties of streamers. In particular, the global symmetry, the height dependence of the proton density is reproduced, and the anti-correlation with heavy ion density is recovered. We plan to expand this study by including nonthermal sources, such as resonant and non-resonant waves, and turbulence to study slow solar wind in multi-ion streamers.

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