A GLOBAL NUMERICAL 3-D MHD MODEL OF THE SOLAR WIND

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Abstract. A fully three-dimensional, steady-state global model of the solar corona and the solar wind is developed. A numerical, self-consistent solution for 3-D MHD equations is constructed for the region between the solar photosphere and the Earth's orbit. Boundary conditions are provided by the solar magnetic field observations. A steady-state solution is sought as a temporal relaxation to the dynamic equilibrium in the region of transonic flow near the Sun and then traced to the orbit of the Earth in supersonic flow region. The unique features of the proposed model are: (a) uniform coverage and self-consistent treatment of the regions of subsonic/sub-Alfvénic and supersonic/super-Alfvénic flows, (b) inferring the global structure of the interplanetary medium between the solar photosphere and 1 AU based on large-scale solar magnetic field data. As an experimental test for the proposed technique, photospheric magnetic field data for CR 1682 are used to prescribe boundary condition near the Sun and results of a simulation are compared with spacecraft measurements at 1 AU. The comparison demonstrates a qualitative agreement between computed and observed parameters. While the difference in densities is still significant, the 3-D model better reproduces variations of the solar wind velocity than does the 2-D model presented earlier (Usmanov, 1993).

1. Introduction

The presence of the solar magnetic field is considered of fundamental importance in the process of the solar wind acceleration. The magnetic field adds structure to the interplanetary plasma and takes an important part in flow energetics. In order to simulate the plasma-magnetic field interaction and to infer the flow geometry self-consistently, numerical MHD studies have been commonly used over the last two decades (see review by Dryer, Smith, and Wu, 1988) evolving from a 2-D, steady-state streamer simulation by Pneuman and Kopp (1971) up to the fully 3-D, time-dependent Interplanetary Global Model developed by Han, Wu, and Dryer (1988).

From both physical and mathematical points of view there are two essentially different regions in the solar wind. The first one is the near-Sun region extending up to 5–10 \( R_s \) (\( R_s \) is the solar radius), where the solar wind is subsonic and sub-Alfvénic, and magnetic forces dominate the flow. In the second region, extending beyond the distance of 5–10 \( R_s \), the flow becomes supersonic and super-Alfvénic, while the magnetic pressure becomes negligible. According to that separation, there exist two approaches to the problem of self-consistent MHD simulation of the solar wind structure. In the first one, transonic/trans-Alfvénic flows near the Sun, inside the sphere of 5–15 \( R_s \), are considered. Only simple model configurations of the magnetic field (mainly of the dipolar type) were studied in the framework of this approach in the 2-D formulation by Pneuman and Kopp (1971), Endler (1971), Steinolfson, Suess, and Wu (1982), Robertson (1983), Washimi, Yoshino, and Ogino (1987), Cuperman, Ofman, and Dryer...
(1990), and in 3-D by Pisanko (1985a, b), Linker, Van Hoven, and Schnack (1990), and Wu and Wang (1991). The second approach studies the solar wind flows in the supersonic and super-Alfvénic regime. In such cases arbitrary initial conditions can be imposed at a starting level placed usually at 18–35 $R_s$. There is an extensive literature of 2-D models and only a few approaching the fully 3-D formulation (Pizzo, 1982; Han et al., 1984; Han, Wu, and Dryer, 1988). Note that we refer above only to multi-dimensional studies. They do not assume spherical symmetry, which allows them to consider the formation of a nonhomogeneous solar wind. At the same time, there exist spherically-symmetrical MHD models (Weber and Davis, 1967; Steinolfson and Dryer, 1984) covering the full range of distances from the Sun to the Earth.

The first attempt to construct a global model describing the solar wind flow and the IMF structure in the whole region between $1 R_s$ and $1 AU$ seems to be that by Usmanov (1993, hereafter referred to as Paper I). A two-region, steady-state MHD model adjusted for the ecliptic plane was developed. The essential new features of the technique proposed in Paper I were also the incorporation of photospheric magnetic field data to prescribe boundary conditions and comparison of computed parameters with those observed by spacecraft for a selected Carrington rotation. However, the two-dimensional nature of that model was its obvious disadvantage because the meridional gradients of dependent variables in the ecliptic plane were assumed to be negligible. While it seems to be a reasonable assumption if the heliospheric current sheet (HCS) is strongly warped and nearly normal to the ecliptic plane near the intersection points, it fails to be appropriate when the HCS is only slightly inclined near the points or weakly deviates from the ecliptic plane (especially during quiet phases of solar cycles).

The purpose of this paper is to present a fully three-dimensional generalization of the 2-D formulation of Paper I. The general concept of the 3-D model is similar to that of the 2-D one, but now we have no need of any assumptions of space symmetry and the region under consideration is all the interplanetary space in the spherical shell bounded by the solar surface from the inside and by a sphere of radius $1 AU$ from the outside.

2. Model Formulation

2.1. Governing Equations

We assume the solar wind plasma to be a single-fluid, inviscid, polytropic gas with infinite conductivity. Interplanetary space is subdivided into two regions. Region I of transonic/trans-Alfvénic flow is assumed to lie between the solar surface and the sphere $r = 9.8 R_s$, and region II of supersonic/super-Alfvénic flow extends beyond this boundary. In heliocentric spherical coordinates with the polar axis along the solar rotation axis, the dissipationless, time-dependent 3-D MHD equations (Lundquist equations) are

$$\frac{1}{S_h} \frac{\partial}{\partial t} (r^2 \rho) = - \frac{\partial}{\partial r} (r^2 \rho u_r) - \frac{r}{\sin \theta} \frac{\partial}{\partial \theta} (\sin \theta \rho u_{\theta}) - \frac{r}{\sin \theta} \frac{\partial}{\partial \phi} (\rho u_{\phi}), \quad (1a)$$