SOLAR WIND STRUCTURE DURING
SOLAR MAXIMUM (1979):
MODEL CALCULATIONS AND
COMPARISON WITH SPACECRAFT DATA

A. V. Usmanov*, J. M. Fritzer** and B. P. Besser**

Abstract

We present results of modeling the global scale, steady-state solar wind structure during the maximum of solar cycle 21 in year 1979. The simulation is based on a 3-D solar wind model which includes Alfvén waves as an additional source of acceleration and heating of the solar wind (Usmanov, 1995; Usmanov et al., 1995). The results for Carrington rotation CR 1677 are compared with observations of the solar wind and IMF parameters on board Helios 1, Helios 2, PVO, Voyager 1, Voyager 2 and Earth-orbiting spacecraft. We also compare the computed radial magnetic field component with measurements by PVO and Earth-orbiting spacecraft. The results of our analysis show a general agreement for the radial magnetic field patterns, while the plasma observations match the model results to lesser extent.

1 Introduction

The purpose of the present paper is to apply a 3-D solar wind model (Usmanov, 1995; Usmanov et al., 1995) to simulate the interplanetary medium structure during the maximum of solar cycle 21 in year 1979 and to use multi-spacecraft solar wind observations for testing the simulation output. Photospheric magnetic field observations at the J. M. Wilcox Solar Observatory are the model input, and spacecraft measurements at various heliocentric distances (ranging from ~ 0.5 AU for Helios 1 and Helios 2 to 6.9 AU for Voyager 1) are the test cases for the model output.

* Institute of Physics, University of St.-Petersburg, St.-Petersburg 198904, Russia
** Institute of Space Research, Austrian Academy of Sciences, Inffeldgasse 12, A-8010 Graz, Austria
2 Model

The MHD-system of equations including Alfvén waves and the mean polytropic flow in a frame of reference corotating with the Sun is approximated by the following set of equations (Jacques, 1977, 1978):

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0, \quad \frac{\partial \mathbf{B}}{\partial t} = \text{rot}(\mathbf{v} \times \mathbf{B}),
\]

\[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} + \Omega \times (\mathbf{v} \times \mathbf{r}) = -\frac{1}{\rho} \nabla P - \frac{GM_\odot}{r^2} \hat{r} + \frac{1}{4\pi \rho} \text{rot} \mathbf{B} \times \mathbf{B} - \frac{1}{2\rho} \nabla \mathcal{E},
\]

\[
\frac{\partial}{\partial t} \left[ \frac{\rho}{2} \left( v^2 - |\Omega \times \mathbf{r}|^2 \right) + \frac{P}{\gamma - 1} + \frac{B^2}{8\pi} - \frac{\rho GM_\odot}{r} + \mathcal{E} \right] =
\]

\[
- \nabla \cdot \left\{ \left[ \frac{\rho}{2} \left( v^2 - |\Omega \times \mathbf{r}|^2 \right) + \frac{\gamma P}{\gamma - 1} - \frac{\rho GM_\odot}{r} \right] \mathbf{v} + \frac{\mathbf{B}}{4\pi} \times (\mathbf{v} \times \mathbf{B}) + \left( \frac{3}{2} \mathbf{v} + \mathbf{V}_A \right) \mathcal{E} \right\},
\]

\[
\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot [(\mathbf{v} + \mathbf{V}_A) \mathcal{E}] + \frac{\mathcal{E}}{2} \nabla \cdot \mathbf{v} = 0,
\]

where \( \rho, \mathbf{v}, \mathbf{B}, P \) and \( \mathcal{E} \) are the density, velocity, magnetic field and Alfvén wave energy density; \( t, \gamma, G, M_\odot, \Omega, \mathbf{V}_A \) and \( \hat{r} \) are the time, polytropic index, universal gravitational constant, solar mass, solar rotation rate, Alfvén velocity and a unit vector in the radial direction, respectively.

In order to obtain a steady-state solution for these equations, we employ a time-relaxation technique: starting from an initial state, the governing equations are integrated in time until a steady state is achieved (i.e. temporal variations of the solution become negligible). At \( t = 0 \), the magnetic field is assumed to be purely radial and to decrease with \( r^{-2} \), while its distribution at \( 1 R_\odot \) is calculated by using spherical expansion coefficients (Hoeksema and Scherrer, 1985) truncated at the 3rd order terms. The distribution of the plasma parameters at \( t = 0 \) is derived from a 1-D solution of the solar wind equations, which is a generalization of Parker’s solution with inclusion of Alfvén waves:

\[
\rho u_r \frac{du_r}{dr} + \frac{d}{dr} \left( P + \frac{\mathcal{E}}{2} \right) + \frac{\rho GM_\odot}{r^2} = 0,
\]

\[
r^2 \left[ u_r \left( \frac{\rho u_r^2}{2} + \frac{\gamma P}{\gamma - 1} - \frac{\rho GM_\odot}{r} \right) + \left( \frac{3}{2} u_r + V_{Ar} \right) \mathcal{E} \right] = F_T,
\]

\[
r^2 \rho u_r = \Phi, \quad \mathcal{E} = \mathcal{E}_0 \frac{V_{Ar}^2 (u_r^0 + V_{Ar}^0)^2}{V_{Ar}^0 r^2 (u_r + V_{Ar})^2},
\]

where \( \Phi \) and \( F_T \) are the mass and energy fluxes per unit solid angle and \( r \) is the radial coordinate. \( u_r^0, V_{Ar}^0 \) and \( \mathcal{E}_0 \) are the mass velocity, Alfvén velocity and Alfvén wave
energy density at $r = r_0$. If we set $r_0 = 1 R_{\odot}$, then the wave energy density flux, $F_w = (\frac{3}{2} u_r^0 + V_{Ar}^0)\mathcal{E}_0$, varies from $10^5$ ergs cm$^{-2}$ s$^{-1}$ at $r = 1 R_{\odot}$ to zero at the outer heliosphere. Quantitatively, we assume that $F_w \sim \delta$, where

$$\delta = (B_{r0}/B_{r0}^{max})^2,$$

and $B_{r0}^{max}$ is the peak value of $B_{r0}$ for the solar rotation under consideration. We assume also that the mass flux $\Phi$ varies with $\Phi \sim \delta$, from $1.76 \cdot 10^{11}$ g s$^{-1}$sr$^{-1}$ when $\delta = 1$ to $1.24 \cdot 10^{11}$ g s$^{-1}$sr$^{-1}$ when $\delta = 0$ (Jacques, 1978). Examples of this 1-D solution are given in Figure 1 and in Table 1. $T_0$ and $B_0$ are the plasma temperature and magnetic field strength at $1 R_{\odot}$.

<table>
<thead>
<tr>
<th>$r$</th>
<th>$F_w$</th>
<th>$u_r$</th>
<th>$\rho$</th>
<th>$\mathcal{E}$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\odot}$/AU</td>
<td>ergs cm$^{-2}$ s$^{-1}$</td>
<td>km s$^{-1}$</td>
<td>cm$^{-3}$</td>
<td>dyn cm$^{-2}$</td>
<td>dyn cm$^{-2}$</td>
</tr>
<tr>
<td>1 $R_{\odot}$</td>
<td>$10^5$</td>
<td>9.9</td>
<td>2.2$\cdot 10^4$</td>
<td>1.1$\cdot 10^{-3}$</td>
<td>1.1$\cdot 10^{-2}$</td>
</tr>
<tr>
<td>1 AU</td>
<td>769.5</td>
<td>6.1</td>
<td>1.3$\cdot 10^{-9}$</td>
<td>4.9$\cdot 10^{-10}$</td>
<td></td>
</tr>
<tr>
<td>1 $R_{\odot}$</td>
<td>0</td>
<td>2.0</td>
<td>9.3$\cdot 10^4$</td>
<td>0</td>
<td>4.6$\cdot 10^{-2}$</td>
</tr>
<tr>
<td>1 AU</td>
<td>300.1</td>
<td>13.4</td>
<td>0</td>
<td>1.0$\cdot 10^{-9}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Numeric values of the 1-D solar wind flow including Alfvén waves for two different wave energy fluxes at the coronal base ($1 R_{\odot}$) and at Earth distance (1 AU)

3 Simulation Results and Discussion

The computational domain for the simulation starts at the coronal base ($1 R_{\odot}$) and extends outwards to 8 AU, covering the locations of several spacecraft measuring the solar wind plasma and magnetic field parameters. To test the simulation results, we use data from Helios 1, Helios 2, PVO, Voyager 1, Voyager 2 and measurements from Earth-orbiting
spacecraft obtained during year 1979 (NSSDC Heliospheric CD-ROM Data Base, 1994). The orbits of these spacecraft projected onto the equatorial plane of the heliographic inertial coordinate system (HGI) are shown in Figure 2. During 1979, all five spacecraft were located within ±7.25° of the equatorial plane.

The computed values and the observed solar wind parameters for Carrington rotation CR 1677 (7 January – February 3, 1979) along the orbits of Helios 1, Helios 2, Earth, PVO, Voyager 1 and Voyager 2 are presented in Figure 3 and Figure 4. Solar wind speed $V$, radial magnetic field component $B_r$, number density $n$ and plasma temperature $T$ are plotted versus Carrington longitude. The numerical simulation is performed on a discrete mesh with a resolution of 12° in both latitude and longitude, while the spacing in radial direction increases proportionally to $r$ from $\Delta r = 0.1 \ R_\odot$ at $1 \ R_\odot$. A 3-D linear interpolation procedure has been applied to calculate the variation of the plasma parameters along the spacecraft orbits. As can be seen from Figure 3 and Figure 4, there is good agreement between the simulated and the measured magnetic field and there is some similarity in the variation of the solar wind velocity. The computed values of $n$ and $T$ are obviously too large to match the observed magnitudes.

Computations similar to those performed for CR 1677 were repeated for the other twelve Carrington rotations of year 1979. The results for the radial magnetic field are shown in Figure 5. The left panel presents the computed variation of $B_r$ along the Earth’s orbit for CR 1677 to CR 1689 (30 November – 27 December 1979) with the observed values superimposed. The right panel displays $B_r$ along the orbit of the Pioneer Venus Orbiter PVO. Keeping in mind the 12 °angular resolution of the model computation (which corresponds approximately to a time resolution of one day) and considering that
4 Conclusion

In this paper, we presented the results of a numerical simulation based on a 3-D solar wind model and compared them with spacecraft observations at locations ranging from 0.5 AU to about 7 AU. The fact that the model is more successful in predicting the magnetic field than in predicting of plasma parameters, possibly, reflects our better knowledge of boundary conditions for the magnetic field at the coronal base. While we use magnetic field observations of the solar photosphere for prescribing the magnetic field boundary values, we had to make some assumptions to specify the boundary condition for the hydrodynamic parameters. However, since the model computations are at least partially successful, this justifies the assumptions made and allows us to infer information about the plasma characteristics at the base of solar corona.

Acknowledgements

We thank Dr J. T. Hoeksema for providing the expansion coefficients of the photospheric
Figure 4: Simulated and observed solar wind and IMF parameters for Earth-orbiting spacecraft (OMNI data), PVO, Voyager 1 and Voyager 2 during Carrington rotation CR 1677
magnetic field observations at the John M. Wilcox Solar Observatory (Stanford). The Interplanetary Medium Data were obtained from the National Space Science Data Center at the Goddard Space Flight Center. The research by AVU described in this publication was made possible in part by Grant No. R61000 from the International Science Foundation, Grant No. R61300 from the International Science Foundation and from the Russian Government, and by Grant No. 93-05-9082 from the Russian Foundation for Fundamental Research. The work of BPB and JMF has been supported by a grant of the Jubiläumsfonds der Österreichischen Nationalbank (No. 5140). AVU wishes to thank the Austrian Academy of Sciences and the Space Research Institute for financial support during his exchange visits.

References


