BRIEF COMMUNICATIONS

MHD Projection Toward the Sun of a Solar Wind Structure Observed at the Earth's Orbit

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This paper shows that numerical MHD modeling can be used for the inverse projection of actual profiles for parameters of the solar wind from the earth's orbit to a distance of ~0.16 AU.

1. The approximation of constant velocity in projecting toward the sun the solar wind speed observed at the earth's orbit can lead to large errors, at least for the leading fronts of high-velocity fluxes. In this paper numerical MHD modeling is applied for the first time to re-calculating the actual profiles of the parameters for the solar wind from the earth's orbit to a distance of 35 Rs from the sun.

2. The theoretical basis for the applicability of numerical models in the reverse projection toward the sun of the solar wind structures observed at the earth has been given in [1], where the following necessary assumptions have been formulated.

1) The observed picture for the parameters of the solar wind and interplanetary magnetic field at the orbit of the earth is stationary in a coordinate system rotating with the sun, i.e., we exclude from consideration all non-stationary processes (for example, flare fluxes).

2) There are no strong shock waves. This assumption is related to the fact that a strong shock wave is an essentially dissipative and, as a result, irreversible process.

We consider a two-dimensional stationary MHD-flow in the equatorial plane of an inertial spherical coordinate system. We will assume that this plane matches the plane of the ecliptic and simultaneously the plane of the helioequator. Solar rotation in the stationary case can be taken into account by substituting into the equations describing the nonstationary case the partial derivative with respect to time for the partial derivative with respect to azimuthal coordinate: \( \partial / \partial t = \Omega / \partial \phi \), where \( \Omega \) is the angular rotation rate for the sun. An additional condition making it possible to decrease the number of equations (substitute the induction equation for the divergence-free magnetic field equation) is the condition for the absence of a stationary electric field in a rotating coordinate system:

\[ u_r B_{\phi} = (u_{\phi} - \Omega) B_r \]

or, alternatively, the requirement for the parallel nature of the velocity and magnetic field vectors. We write out the system of divergence-free MHD-equations for this two-dimensional problem in conservative form:

\[
\begin{align*}
\frac{\partial}{\partial r} \left( \rho r^2 u_r \right) &= - \frac{\partial}{\partial \phi} \left( \rho u_{\phi} \right) \\
\frac{\partial}{\partial r} \left( \rho r^2 u_{\phi} \right) &= - \frac{\partial}{\partial r} \left( \rho u_{\phi} \right) - \frac{B_r B_{\phi}}{4 \pi} - r \left[ \frac{B_r}{\rho} \left( \gamma - 1 \right) - \frac{B_r}{4 \pi} \right] \\
\frac{\partial}{\partial r} \left( \rho u_r u_{\phi} \right) &= - \frac{\partial}{\partial r} \left( \rho u_{\phi} \right) + \frac{\rho}{4 \pi} \frac{B_r B_{\phi}}{r} + \frac{B_r^2 - B_{\phi}^2}{4 \pi} \\
\frac{\partial}{\partial r} \left( \rho r^2 B_r \right) &= - \frac{\partial}{\partial \phi} \left( \rho B_{\phi} \right) \\
\frac{\partial}{\partial r} \left( \rho r^2 B_{\phi} \right) &= - \frac{\partial}{\partial \phi} \left( \rho B_r \right) \\
\frac{\partial}{\partial r} \left( \frac{1}{2} \left( \rho U_r \gamma + \frac{u_r}{2} \right) - \omega \frac{B_r B_{\phi}}{4 \pi} \right) &= 0
\end{align*}
\]

where the independent variables \( U_r \) and \( U_{\phi} \) are the radial and azimuthal components of the velocity, \( B_r \) and \( B_{\phi} \) are the radial and azimuthal components of the magnetic field, \( \rho \) is the density, \( P \) is the plasma pressure, \( \omega \) is the linear rotational velocity at a distance \( r \)

\[ (\omega = \Omega r) \]

and \( V_{\phi} \) is the azimuthal velocity in the rotating coordinate system

\[ \left( V_{\phi} = U_{\phi} - \omega \right) \]
Solar wind speeds (ν) observed at the earth's orbit (solid lines) and recalculated to 35 \( R_S \) (dashed lines), along with the magnetic field radial component (\( B_R \)) and concentration (\( n \)). Dot-dash line indicates the inverse projection of the solar wind speed in the constant velocity approximation.

3. The existence of observational data for the parameters of the plasma near the earth [2] makes it possible to give the distribution of dependent variables for the chosen time interval at the initial level (the earth's orbit). To do this the following procedure is used. Mean daily values calculated from the data [2] are given at the nodes of the initial 13-degree grid (13° is the revolution angle of the sun in one day), which it then transformed to a finer 3.25-degree grid. The values of the additional nodes are determined by linear interpolation of the daily values, after which there is an eightfold three-point smoothing of the 3.25° grid. This procedure makes it possible to eliminate the high-frequency part of the variations in the solar wind parameters with a period of 1-2 days, due mainly to nonstationary processes of flare nature in the solar wind.

In the figure, the solid lines indicate the initial distributions for the velocity, radial component of the interplanetary magnetic field (IMF) and density of the solar wind for the interval from January 1 to February 23, 1973 (Bartels cycles 1907-1908). The initial pressure distribution is given in accordance with the measured values for the concentration (\( n \)) and temperature (\( T \)) from the equation of state:

\[ \rho = 2 \, n k T \] (where \( k \) is the Boltzmann constant). It is also assumed that the polytropic exponent is \( \gamma = 1.17 \) [3] and \( \nu_{\infty} = 0 \) at the initial level.

Proceeding from the initial level, the solution is constructed by advancing in the negative (toward the sun) direction for the radial coordinate. Since the solved system of equations is hyperbolic only in the region of supersonic and super-Alfvén solar wind flow, the solution cannot be brought to the surface of the sun, where the flow is subsonic. We have chosen the limiting value of 35 \( R_S \) (0.16 AU).

The system of Eqs. (1) was integrated numerically using a two-step MacCormack scheme [4]. The spacing in the radial coordinate was chosen from the Courant-Friedrichs-Levy condition at each integration step.

The results of the calculations for the flow parameters at 35 \( R_S \) are represented by dashed lines in the figure. In the figure (a) the dot-dashed line also drawn is the curve for the reverse projection to 35 \( R_S \) of the solar wind velocity in the constant velocity approximation. Comparison of the results for the reverse projection using the numerical model and in the constant velocity approximation shows they have good agreement. The largest differences occur for the leading fronts of the flow—the difference is about a day, while the following fronts match very well. The values for the velocity in the numerical projection are somewhat less than is explained naturally by taking into account the increase in the solar wind speed with distance from the sun.

In the distribution of the radial component of the magnetic field at 35 \( R_S \) we note the flattening out of its profile at the leading fronts of the high-velocity flows because of "dissipation" of the region of interaction as the sun is approached.

4. Therefore, the application of numerical MHD models permits, on the one hand, refining the approximation of constant velocity for the reverse projection of velocity structures of the solar wind and, on the other hand, obtaining information about the parameters of the interplanetary plasma (density, pressure, temperature, and magnetic field) at much closer distances to the sun than the earth's orbit. In prospect it is possible to check these results by comparing them with data from Helios satellites.

Data on the parameters of the interplanetary medium have been obtained from the National Center for Space Data through WDC-A (Greenbelt).

REFERENCES


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