Peculiarities of the Interstellar Dust Distribution in the Heliosphere Induced by the Time-Dependent Magnetic Field

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Interstellar dust enters the heliosphere due to the relative motion of the Sun and the Local Interstellar Cloud, which contains the Sun. The dynamics of interstellar dust particles is governed mainly by the electromagnetic force. The direction of this force depends on the polarity of the heliospheric magnetic field. In turn, polarity is a function of position and time and depends on the orientation of the solar magnetic dipole axis relative to the solar rotation axis. Previously it was shown that for the case when the magnetic dipole axis coincides with the solar rotation axis, the electromagnetic force acting on dust particles is directed towards the solar equatorial plane in both the northern and southern solar hemispheres. As a result, under the influence of such a force, the distribution of interstellar dust becomes highly inhomogeneous and, in particular, thin regions of increased number density (caustics) are formed. The goal of this work is to study the nature of caustics for a more realistic time-dependent model, when it is assumed that the magnetic dipole axis rotates relative to the solar rotation axis with a period of 22 years in accordance with the 22-year solar cycle. In addition, the magnetic dipole axis rotates due to the rotation of the Sun with a period of 25 days. To calculate the dust number density, the Lagrangian Osiptsov method is used. The shape and evolution of the resulting caustics are examined and the physical mechanisms of their origin are discussed. It is shown that, when taking into account time-dependent effects, caustics appear only in certain phases of the 22-year solar cycle, and then disappear.

Keywords: interstellar dust, heliosphere, lagrangian approach

The solar wind, flowing from the solar corona, becomes supersonic at several solar radii and interacts with the supersonic plasma flow of the local interstellar medium (LISM). As a result, a structure of two shock waves and a tangential discontinuity between them is formed [1]. Figure 1 shows the schematic view of the interaction between the solar wind and the LISM plasma. The region of solar wind propagation limited by the tangential discontinuity (heliopause) is called the heliosphere....

1. METHOD

To model the distribution of ISD particles usually the Monte Carlo method is used [see, for example, 2], but for studying the peculiarities this method is ineffective from a computational point of view, therefore, in this work we apply the Lagrangian Osiptsov method [3]. The Lagrangian method is based on solving the continuity equation written in Lagrangian coordinates:

$$n_d(t, \mathbf{r}_0)|\det(J_{ij}(t, \mathbf{r}_0))| = n_d(0, \mathbf{r}_0), \tag{1.1}$$

where $\mathbf{r}_0 = (x_0, y_0, z_0) = (x_{1,0}, x_{2,0}, x_{3,0})$ are the Lagrangian coordinates of the considered particle, $J_{ij} = \frac{\partial x_i}{\partial x_{j,0}}$ are the components of the transition matrix from Lagrangian to Eulerian coordinates (Jacobian matrix). This equation is valid along the trajectory of a Lagrangian particle (dust particle, in this case). Accordingly, in order to calculate the dust number density at an arbitrary point along the trajectory, it is necessary to determine the components of the Jacobian matrix at this point.

To calculate the components of the Jacobian matrix one need to introduce the matrix $\Omega_{ij} = \frac{\partial J_{ij}}{\partial t}$ and formulate additional differential equations for the components of this matrix. As a result, for each fixed particle, we can obtain the following Cauchy problem:

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$$
\begin{cases}
\frac{dx_i}{dt} = v_i, \\
\frac{dv_i}{dt} = F_i, \\
\frac{dJ_{ij}}{dt} = \Omega_{ij}, \\
\frac{d\Omega_{ij}}{dt} = \sum_{k=1}^{3} \frac{\partial F_i}{\partial x_k} J_{kj}
\end{cases}
,
\begin{cases}
\mathbf{r}|_{t=t_0} = \mathbf{r}_0, \\
\mathbf{v}|_{t=t_0} = -v_{LISM}\mathbf{e}_y, \\
J_{ij}|_{t=t_0} = \delta_{ij}, \\
\Omega_{ij}|_{t=t_0} = 0
\end{cases}
\tag{1.2}
$$

where δ_{ij} is the Kronecker delta.

By solving the Cauchy problem (1.2), one can calculate the Jacobian at any point along the trajectory of the given particle and obtain the value of the dust number density at this point from the equation (1.1). However, to do this, first of all, it is necessary to define forces acting on ISD particles in the heliosphere.

2. MODELING RESULTS

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2.1. Stationary Focusing Heliospheric Current Sheet

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2.2. Time-Dependent Heliospheric Current Sheet

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CONCLUSIONS

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Figure 1: The schematic view of the interaction between the supersonic solar wind and the local interstellar medium plasma. Black and red arrows match the streamlines of the solar wind and interstellar plasma, correspondingly. Blue arrows show the direction of ISD flow in the undisturbed local interstellar medium. *TS* – heliospheric termination shock, *HP* – heliopause, *BS* – interstellar bow shock.

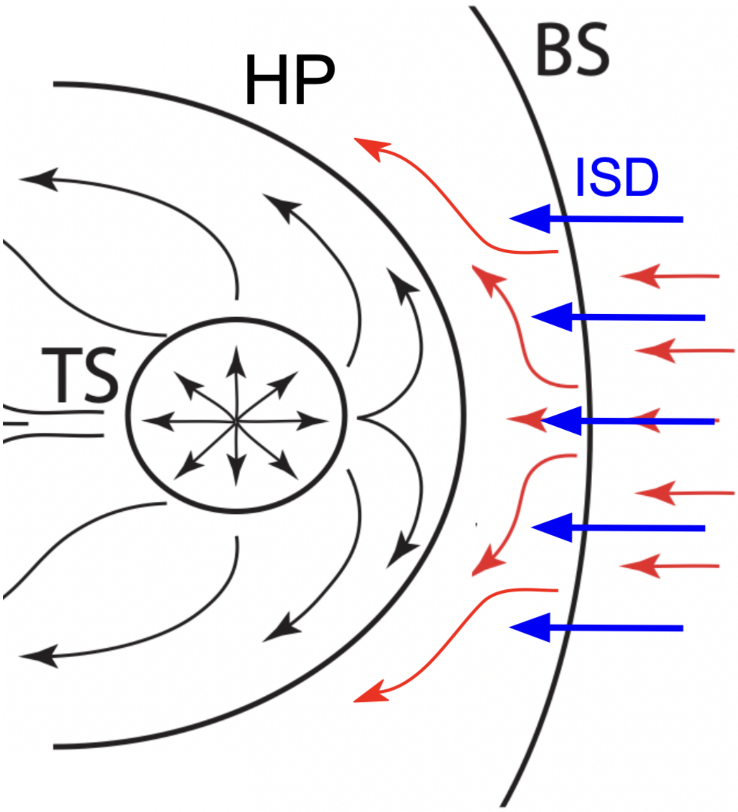

Figure 1.