GLOBAL MODELING OF DISTURBANCES IN THE CORONA-INTERPLANETARY SPACE

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In the past few years, numerical studies of corona-interplanetary dynamics have been undertaken by many investigators. The results, as summarized by Wu et al. (1977), indicate that this approach seems very promising and worthy of further pursuit. So far, the calculations have been performed on two-dimensional codes, to simulate magneto-hydrodynamic flow in a meridional plane or in the equatorial plane. In order to fully account for the global features of the corona-interplanetary phenomenon, it is necessary to do three-dimensional calculations. Here we discuss some groundwork for the formulation of a time-dependent three-dimensional code.

To describe the physical phenomenon of the complicated disturbances in the corona-interplanetary space by mathematical solutions of an idealized initial-boundary value problem, it is necessary to use various approximations. If the solution is to be physically meaningful, the approximations used must be physically reasonable. This means a judicious choice of the governing equations and the initial-boundary conditions, with as few ad hoc parameters as possible. The governing equations represent the physical laws, according to them the corona-interplanetary medium undergoes changes from the state indicated by the initial condition, subject to the constraint indicated by the boundary condition. A part of the initial-boundary conditions specifies the source of disturbance. Of course, to find the solution explicitly, a stable computation scheme has to be devised, so that the numerical solution obtained is acceptably accurate.

The corona-interplanetary space has a spatial domain extending from the coronal base to the outreach of the heliosphere. In the length scale pertinent to the global phenomenon , the inner boundary can be represented by a spherical solar surface and the outer boundary by

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a heliocentric sphere of very large radius. Beneath the inner boundary is the active subphotospheric sun, and beyond the outer boundary is the passive interstellar medium. Effluxes of mass, energy, momentum, and magnetic flux from the sun are transported by the corona-interplanetary medium into the interstellar space.

A one-fluid description for the corona-interplanetary plasma is appropriate for the large-scale global features. Thus, there are four primary physical quantities, namely, mass density, temperature, flow velocity, and magnetic field. Their temporal changes are governed by conservation laws of mass, energy, and momentum and Faraday's law of induction. These four physical laws can be written as partial differential equations which relate the temporal derivatives to various spatial derivatives. Other physical quantities, namely, plasma pressure, specific thermal energy, current density, and electric field, are secondary in the sense that they can be expressed in terms of the primary quantities. The auxiliary equations, viz., equation of state, a thermodynamic equation, Ampere's law with the displacement current neglected, and Ohm's law with a scalar resistivity, involve no temporal derivatives at all. The energy equation should include heat conduction and ohmic dissipation. The former is an important process of energy transport in the corona-interplanetary medium, and the latter is necessary for the magnetic diffusion to allow the topological changes between closed and open configurations in the temporal evolution of the magnetic field. As to the equation of motion, the plasma motion is driven by pressure gradient, solar gravitation, and magnetic force. The equation of induction will preserve the solenoidality of the magnetic field.

We envisage the disturbance as ensued from some sort of local instability. Prior to the onset of the disturbance, the corona-interplanetary medium is in a steady state, transporting the effluxes from the sun to the interstellar medium. In this quiescent process, somehow excessive amounts of mass, energy, momentum, or magnetic flux are gradually built up in some localized region. If the region of instability is located above the coronal base, the source of disturbance is accounted for by the initial condition for that part of the corona-interplanetary space. On the other hand, if the region of instability is located below the coronal base, the source of disturbance is accounted for by the boundary condition for a part of the inner boundary where the excessive effluxes enter the corona-interplanetary space. Other parts of the corona-interplanetary space have the quiescent initial condition and other parts of the boundaries have the quiescent boundary condition. The localized instability is only strong enough to affect a smal part of the corona-interplanetary space at the initial instant or a part of the inner boundary for a short while. The unaffected parts remain at the quiescent state. The outer boundary is not affected at all till the arrival of the disturbance. In fact, if the outer boundary is idealized to be at infinity, the boundary condition at infinity is vanishing mass density, temperature, magnetic field and infinite flow velocity. The indefinite effluxes at this passive boundary are determined by the solar wind in the corona-interplanetary space. Therefore, we may pose two kinds of initial-boundary value problem. One has a disturbed initial condition and a quiescent boundary condition. The other has a disturbed boundary condition and a quiescent initial condition. Their mixture will have disturbed parts in both the initial and boundary conditions. With a static initial condition, as assumed in most of the previous work, the inner boundary would become passive . This means that some fluxes are allowed to enter through the coronal base from the corona-interplanetary space.

The quiescent initial-boundary conditions are in turn to be obtained by means of modeling which should utilize the observed solar data as much as possible. At the present time, solar magnetograms provide only the line-of-sight component of the magnetic field at the photospheric level. This is not sufficient to determine the current, hence the current-filled magnetic field, in the steady state corona-interplanetary space. We may use sheet-current approximation (Yeh and Pneuman, 1977), which requires only scalar data on the solar surface, to determine a piecewise current-free magnetic field partitioned by current sheets. The presence of the sheet currents means that the hydromagnetic interaction between the magnetic field and the plasma motion is not entirely ignored. Since small-scale details of the photospheric magnetograms have no bearing on the large-scale features of the corona-interplanetary space, only the large-scale photospheric data should be extrapolated as the data at the coronal base. The most important feature is the neutral lines. Their nested arrangement on the solar surface determines the magnetic topology of the corona-interplanetary magnetic field (Yeh, 1978). The H-alpha synoptic charts (McIntosh, 1979) are very useful in discerning the relevant neutral lines.

To solve the formulated initial-boundary value problem numerically by finite-difference method, the outer boundary is replaced by a heliocentric sphere of a suitable radius. The boundary condition to be specified at this ad hoc boundary is the quiescent values of the initial steady state. This replacement is valid only prior to the arrival of the disturbance. Hence, it is necessary to move the ad hoc outer boundary farther out once in a while in the course of computation. Likewise, ad hoc lateral boundaries may be used, as in the previous work. Again, the boundary conditions on these ad hoc lateral boundaries are the quiescent values of the initial steady state and the lateral boundaries must be moved and eventually removed as the disturbance spreads laterally. It is advantageous to use spherical coordinates. Special care must be taken at the two polar lines. There the differential operators for gradient, divergence, curl, and trajectory derivative, written in the spherical coordinates, become indefinite in form. A finite-difference approximation for the governing equations can be devised by using the integral forms of these del operators at the grid points located on the polar lines. For the grid points not on the polar lines differential forms will provide the finite-difference approximation. A scheme of third-order accuracy can be constructed by the use of the two-step Lax-Wendroff treatment. The virtual grid points for the intermediate steps may be chosen at the centers of the boxes formed by eight neighboring real grid points. More important than the accuracy is the stability of the scheme. The time step should be less than the values of the local grid spacing divided by the fast magnetoacoustic speed. The inclusion of dissipations in the governing equations should enhance the numerical stability. Since a lot of grid points are needed in such global modeling, a lattice of grid points with uneven spacings will allow the allocation of more grid points to regions where the physical quantities are expected to undergo large variations. We are presently exploring the feasibility of implementation, regarding the huge demand on the storage capacity and computation time, for a three-dimensional code on NCAR's Cray-1 computer.

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