FINAL REPORT ON GRANT NAGW-162

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1.0 Introduction

This is the final report on grant NAGW-162 between the University of California, Los Angeles and NASA. In sections 2 and 3 the results obtained during the final year of the grant have been presented. Results for previous years have been detailed in previous reports. A complete bibliography is presented in section 4.

2.0 A Magnetohydrodynamic model of the interaction of the solal wind with the jovian magnetosphere.

2.1 Scientific Background

It is extremely difficult to understand a magnetospheric system by using the limited measurements provided by a spacecraft during a planetary flyby or even by using the more complete data from an orbiter. In order to understand a magnetospheric system, the experimenter is challenged to interpret his limited single point measurements in terms of a large scale, and highly dynamic system. The immense size and dynamic nature of the jovian magnetosphere greatly complicates this problem. During the past few years a new technique, magnetohydrodynamic (MHD) simulation, has been developed to help solve this problem and to provide a self-consistent picture of the solar wind magnetosphere system.

In an MHD simulation, this plasma is modeled as a conducting fluid and the time-dependent equations for fluid flow plus Maxwell's equations are solved numerically by using finite difference methods. In the finite difference methods, the independent variables are defined on a grid of points over the spatial regions of interest. The spatial derivatives of the equations are approximated by computing between quantities defined on the grid.

Three-dimensional global MHD simulations have been used previously to model the interaction of the supersonic and superalfvenic solar wind with the earth's magnetic field (Leboeuf et al., 1981; Wu et al., 1981; Brecht et al., 1982; Ogino and Walker, 1984) and with comets (Schmidt and Wegmann, 1982; Fedder et al., 1984; 1986 Ogino et al., 1986). Models are being developed to model the interactions of the solar wind with the Venus ionosphere (Brecht and Smith, 1984) and the interaction of the subalfvenic and subsonic jovian plasma with Io (Linker et al., 1986).

The development of an MHD simulation for the case of Jupiter is interesting not only because it will help us to understand the jovian system better, but also because this problem represents a new parameter regime for MHD models. Jupiter's rapidly corotating plasma offers us the opportunity to study the interaction of a planetary wind with the solar wind. This offers us the further opportunity to expand our knowledge to objects of astrophysical interest.

2.2 Progress during the reporting period

During the past year, we have completed the development of a 3D code for a rapidly rotation magnetosphere in which we solve the MHD equations and Maxwell's equations by using the two step Lax Wendroff scheme. The method is similar to the one we used in our most recent model of the earth's magnetosphere (Ogino and Walker, 1984; Ogino et al., 1985; Ogino, 1986; Ogino et al., 1986).

For models of the earth's magnetosphere, the obstacle in the solar wind is the earth's dipole magnetic field. In the jovian model the obstacle is the field and plasma from an equilibrium model of a rapidly rotating magnetodisk. In our calculations, we started with two equilibrium configurations. In both cases, we assumed azimuthal symmetry and that the rotational frequency was a function of the magnetic flux. In the first case, the initial configuration was calculated with $\omega(\psi) = \omega_0\psi^2/(\psi^2 + \psi_0{}^2)$ while $\omega(\psi) = \omega_0\psi/(\psi + \psi_0)$ was used in the second case where ω_0 is Jupiter's rotation frequency, ψ is the magnetic flux and $\psi_0 = \psi(r_c)$ is the flux at the Alven critical radius $r_c = 35\ R_j$ (Jovian radii). The second model gives larger rotational velocities in the outer magnetosphere. In Figure 2.2.1 we have plotted magnetic field lines for the case in which the rotation was greatest. For this case, we chose a rather large value for the solar wind pressure (1×10^9 dynes/cm^2) so that the resulting magnetosphere would fit well within our simulation box. The subsolar point is at 51 Rj. This is similar to the location inferred from the final Voyager 1 encounter with the dayside magnetopause. All in all the configuration is similar to that seen in models of the earth's magnetosphere.

The difference between a magnetosphere where rotation is important and one where it isn't can be more clearly seen in Figure 2.2.2. Here we have plotted pressure contours in the noon-midnight (top) and equatorial planes (bottom) for three model runs, the two corotational models and a case where
$\omega = 0$. The solid curves give the locations of the magnetopause and bow shock. They were determined by examining the magnetic field and flow in addition to the pressure contours. In the noon-midnight meridian the magnetopause shape with rotation is similar to that without. The major differences can be seen in the equatorial plane where the magnetosphere becomes broader as the corotation is increased. The results for the case $\omega = \omega_0\psi/(\psi + \psi_0)$ are in excellent agreement with the magnetopause and bowshock shapes inferred from observations by Slavin et al., (1985).

The pressure pattern in the equatorial plane becomes asymmetric when we add corotation. Note the local pressure maxima in the equatorial plane at 30-40 R_j. The largest of these occurs in the early morning magnetosphere and is associated with intense field aligned currents directed away from the jovian ionosphere. These currents are generated by the pressure gradients associated with this maximum.

In Figure 2.2.3, we have plotted the flow pattern in the noon-midnight and equatorial planes. The effect of corotation is to create a flow vortex on the dawn side. Across this vortex the flow changes from the azimuthal direction to the tailward direction.

Preliminary results from this simulation were presented at the Fall AGU meeting in San Francisco (Walker and Ogino, 1985) and a more complete analysis was presented at the Second Neil Brice Memorial Symposium, "Magnetospheres of the Outer Planets," at the University of Iowa, Iowa City, Iowa, (Walker and Ogino, 1986).

3.0 A magnetohydrodynamic simulation of the interaction of the solar wind with the out flowing plasma from a comet.

3.1 Scientific Background

The interaction of the solar wind with a comet is somewhat different from that of the solar wind with magnetized planets like Mercury, the Earth, Jupiter, Saturn and Uranus. The solar wind interaction with comets also differs from that with unmagnetized planets like Venus. These differences occur because the comet has no intrinsic magnetic field and a very small mass. A large amount of gas is evaporated from the icy nucleus and extends into the solar wind where it is ionized (Mendis and Ip, 1977; Mendis and Houpis, 1984; and Neidner, 1984). Prior to the recent cometary flyby missions, a global model of the solar wind-comet interaction was proposed. When the outflowing plasma from the comet interacts with the solar wind plasma three discontinuities, the outer shock, contact surface and the inner shock, are expected to appear in the sunward comet-solar wind interaction region (Brandt and Mendis, 1979). The outflowing dense plasma from the comet is largely confined to the region inside the contact surface. Alfven (1975) proposed that interplanetary magnetic field (IMF) lines hang up on this cometary plamsa to form a cometary plasma tail in the downstream region.

Observations from the recent missions to comets Giacobini-Zinner and Halley have confirmed many features of this model. All of the missions detected a bow shock like boundary although the exact nature of the boundary is the subject of debate (eg. Bame et al., 1986; Smith et al., 1986; Scarf et al., 1986; Jones et al., 1986; Thomsen et al., 1986; and Neubauer et al., 1986). At comet Halley, the Giotto spacecraft passed through the contact surface (Neubauer et al., 1986) while at Giacobini-Zinner, the ICE observations have confirmed Alfven's model of the magnetotail (Smith et al., 1986; Slavin et al., 1986).

The cometary plasma tail frequently has a complicated structure with narrow rays emanating from the head and kinks and helical waves deeper in the tail (Mendis and Houpis, 1982; Niedner, 1984). In addition, the tail sometimes disconnects and propogates away from the comet (Niedner and Brandt, 1978/1979; Niedner et al., 1981). Several models have been proposed to explain disconnection events including both dayside and nightside reconnection (Ip and Mendis, 1975, 1976; Neidner and Brandt, 1978, 1979; Russell et al., 1986).

As noted in section 2.1 there have been two previous simulation models of comets. Schmidt and Wegmann (1982) have solved the full set of magnetohydrodynamic (MHD) equations to model the interaction between the solar wind and the cometary ionosphere in the region exterior to a fixed contact surface. Fedder et al. (1986a,b) used their code to model the overall structure of the comet tail. They used a three-dimensional (3D) model and included a cometary source of plasma productions.

3.2 Progress during the reporting period

In last year's proposal, we noted that we would begin to adapt our basic simulation model to study the solar wind interactions with other bodies in additions to Jupiter. Because of the recent comet flybys, we have chosen a comet as the first new model. In this first study, we have modeled the dynamics of a cometary plasma. Our aim was to model the formation of the contact surface and the plasma tail.

The comet simulation model is similar to models of the earth's magnetosphere in that we solve the resistive MHD equations as an initial value problem (see section 1.1.1). The major difference between the earth model and the comet model is the obstacle to the solar wind flow. In the cometary case, we must model the outflowing plasma from the comet. The range of scale sizes associated with the comet interaction is from ~10km to ~10^6km. This is a much wider range than that in the earth or Jupiter models. Thus we limited the calculations to two dimensions, modeled only the region within 10^3 R_o (R_o is the radius of the source region of outflowing plasma) and used very dense grid (400 x 100 grid points). We also used a large cometary outflow velocity to reduce the distance between the boundaries. The mesh spacing was $\Delta x = \Delta z = 3R_o$. The time step ($\Delta t$) was $4\Delta\omega/V_A$ where V_A is the Alfven velocity.

In Figure 3.2.1 we have plotted two-dimensional configurations of the density, ρ, the flow velocity, v and the magnetic flux, ψ, for three times. The interplanetary magnetic field (IMF) was held constant throughout the entire calculations. The density is color coded with the largest values in yellow and white. Three density jumps can be recognized at $t = 12t_o$, it is difficult to distinguish between the contact surface and the inner shock. By $t = 10t_o$ - $15t_o$ the IMF has draped over the comet forming a long cometary plasma tail with a thin plasma sheet. Tail magnetic reconnection begins at $t = 15t_o$. Small plasma bubbles or plasmoids containing warm plasma, form in the unstable plasma sheet and propagate down the tail at the local Alfven speed.

In a second run, we held the IMF constant until $t = 9t_o$ and then reversed it. In this case, dayside reconnection occured in addition to tail reconnection. The result was a complex tail with plasmoid forming in both the dayside and nightside reconnection regions and propagation tailward. We presented preliminary results obtained by using this model at the Fall AGU meeting in San Francisco (Coleman et al., 1985) and a paper on more mature results was published in Geophysical Research Letters (Ogino et al., 1986).

Late in the grant period, we began work on a three dimensional model which included the effects of mass loading. This model was designed to study the weak cometary bow shocks observed by the probes to comets

Halley and Giacobini-Zinner. This work was completed after this grant ended by using funding from another source. The model was successful in reproducing the positon and shape of the bow shock which was determined by using observations from the Suisei spacecraft (Mukai et al, 1986). A paper on this work has subsequently been completed and submitted to the Journal of Geophysical Research (Ogino et al, 1987).

Figure Captions

Figure 2.2.1

Jovian magnetic field lines for the case with largest rotational velocity.

Figure 2.2.2

Pressure contours for three different rotation models. The left panels show the case with no corotation while the two models described in the text are plotted in the middle and right columns. Contours are drawn in the noon-midnight meridian in the top panels while the contours in the bottom panels are for the equatorial plane. The heavy curves give the estimated positions of the magnetopause and bow shock.

Figure 2.2.3

Flow vectors for the three different rotational models. The format is the same as Figure 1.1.2.

Figure 3.2.1

Two-dimensional configuration of the plasma density, ρ, the plasma velocity, v. and the magnetic flux, ψ. The density is color coded with largest values in yellow and white.

4.0 Publications

4.1 Papers presented during scientific meetings

Coleman, P.J., T. Ogino, R.J. Walker, M. Ashour-Abdalla, and D.A. Mendis, and MHD simulation of the interaction of the solar wind with outflowing plasmas from a comet (abstract), EOS Trans. AGU, 66 (46), 1021, 1985. Presented at the Fall AGU meeting, San Francisco, 1985.

Hoppe, M.M., C.T. Russell, L.A. Frank, T.E. Eastman, and E.W. Greenstadt, Foreshock structure: Upstream ULF waves and their association with backstreaming ion populations, Presented at the 4th IAGA Scientific Assembly, Edinburgh, August, 1981.

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Walker, R.J. and M.G. Kivelson, The structure of currents in the middle Jovian magnetosphere (Abstract), EOS Trans. AGU, 64(18), 291, 1983. Presented at Spring AGU Meeting, Baltimore, 1983.

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Walker, R.J., and T. Ogino, A magnetohydrodynamic simulation of the interaction of the solar wind with the jovian magnetosphere, abstract volume P3, Presented at the Second Neil Brice Memorial Symposium, "Magnetospheres of the outer planets," University of Iowa, Iowa City, Iowa, 1986.

4.2 Papers published in referred journals

Hoppe, M.M., and C.T. Russell, Planetary bow shock comparisons: Inferences from upstream waves, Nature, 295(41), 5852, 1982.

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4.3 Papers submitted for publication

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Ogino, T., R.J. Walker, M. Ashour-Abdalla, A three dimensional MHD simulation of the interaction of the solar wind with comet Halley, submitted to J. Geophys. Res., 1987.

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Magnetic Field Lines for $\omega = \omega_0 \frac{\psi}{\psi + \psi_0}$

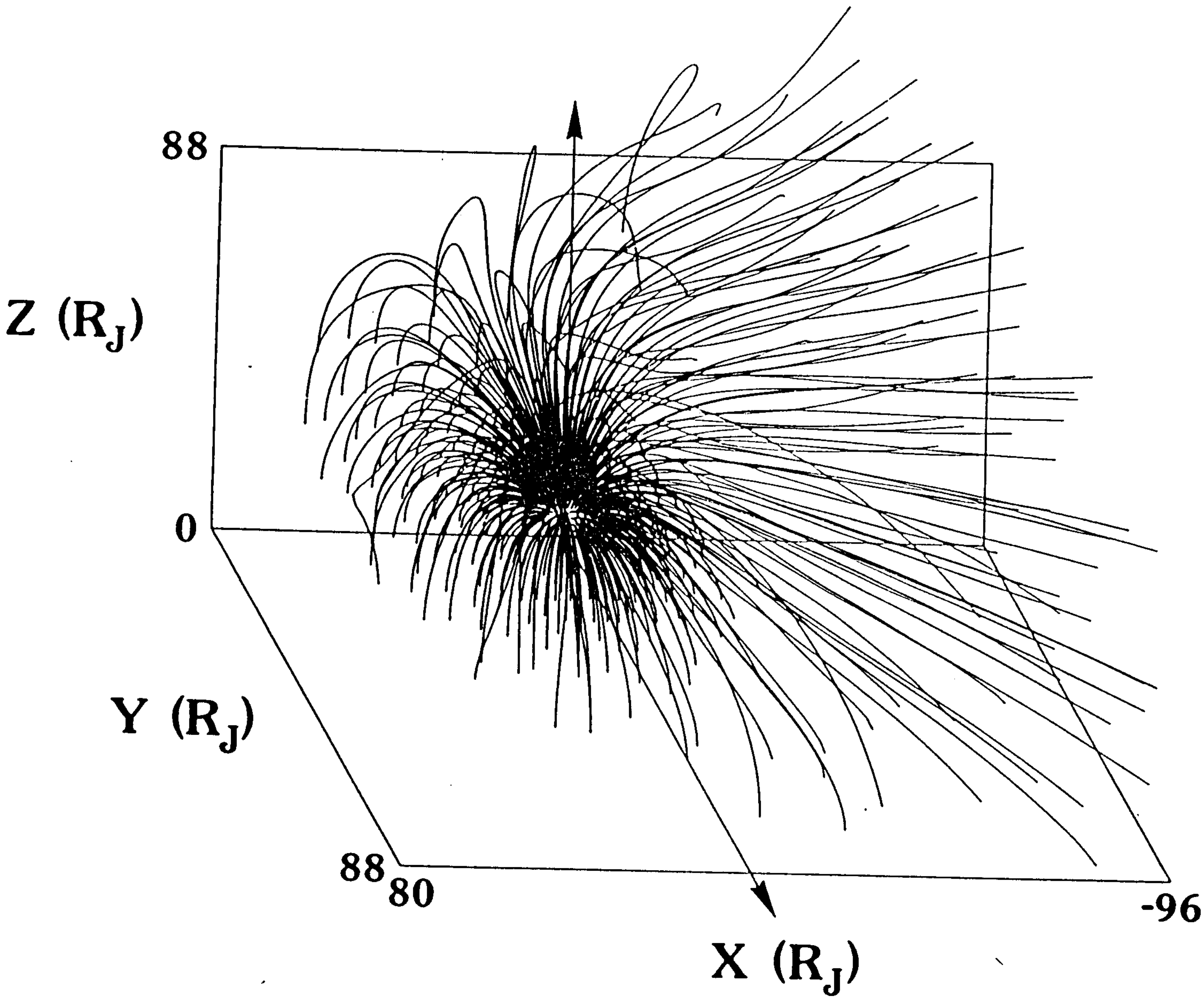

Fig. 2.2.1

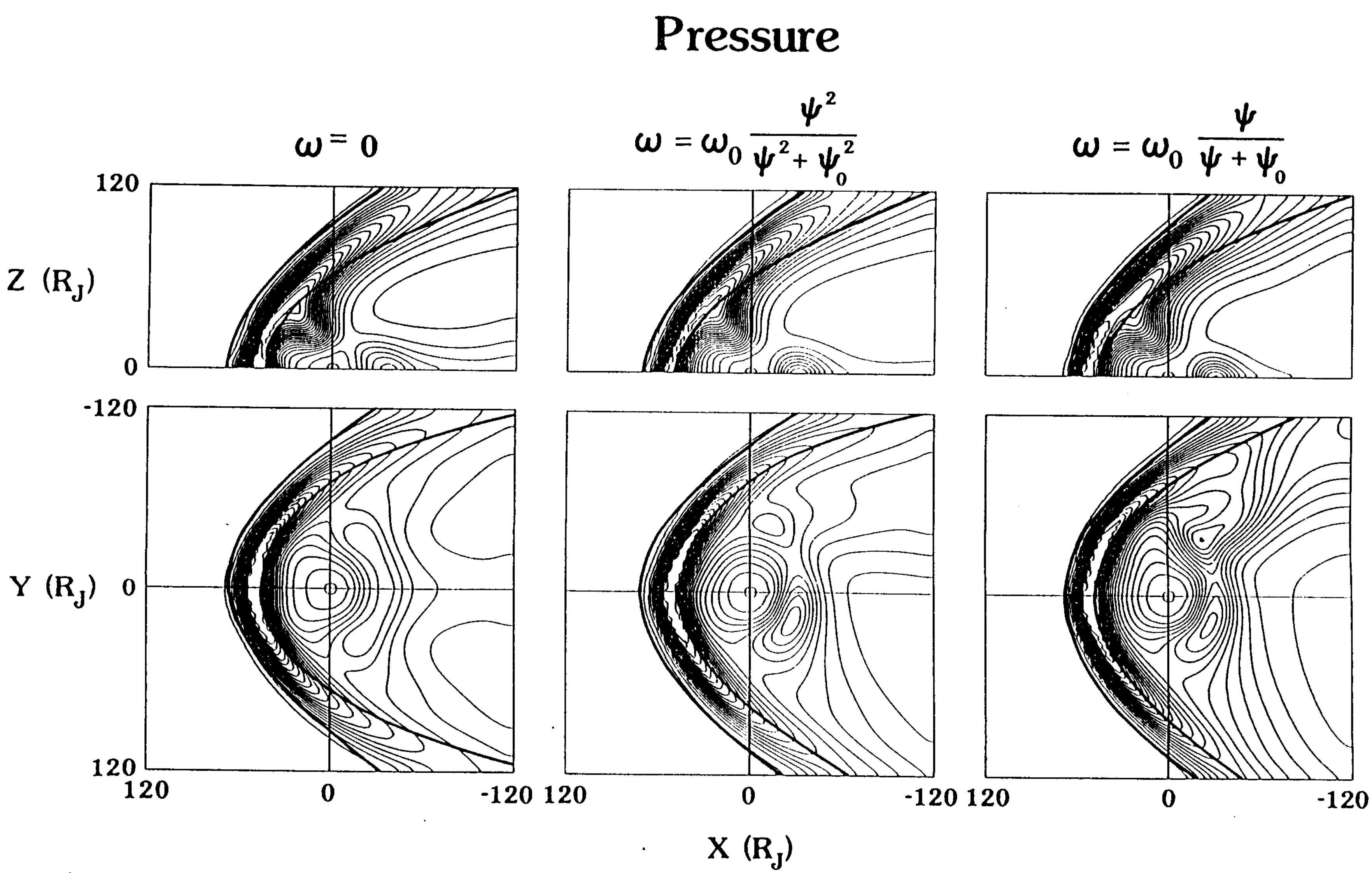
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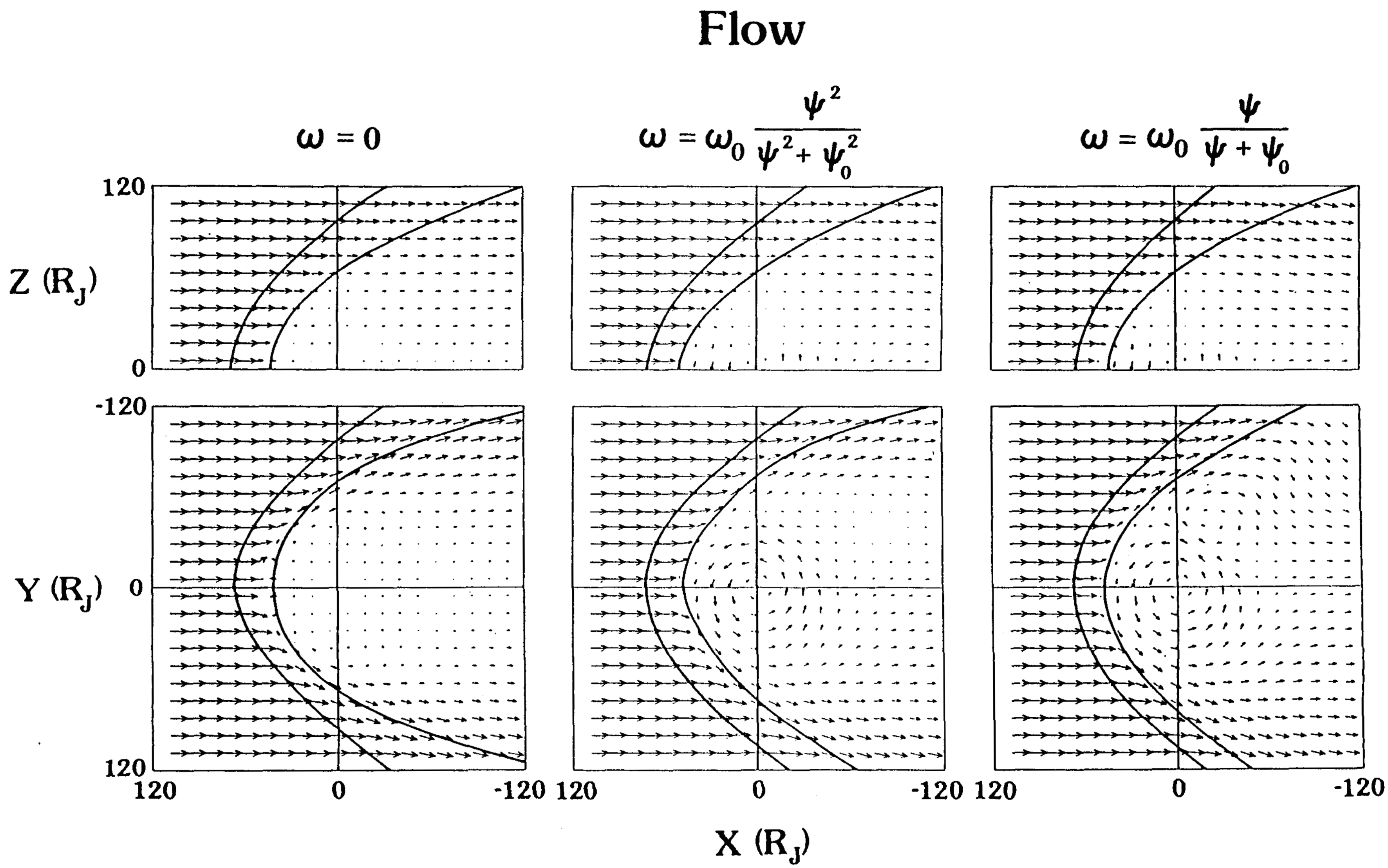
Fig. 2.2.2



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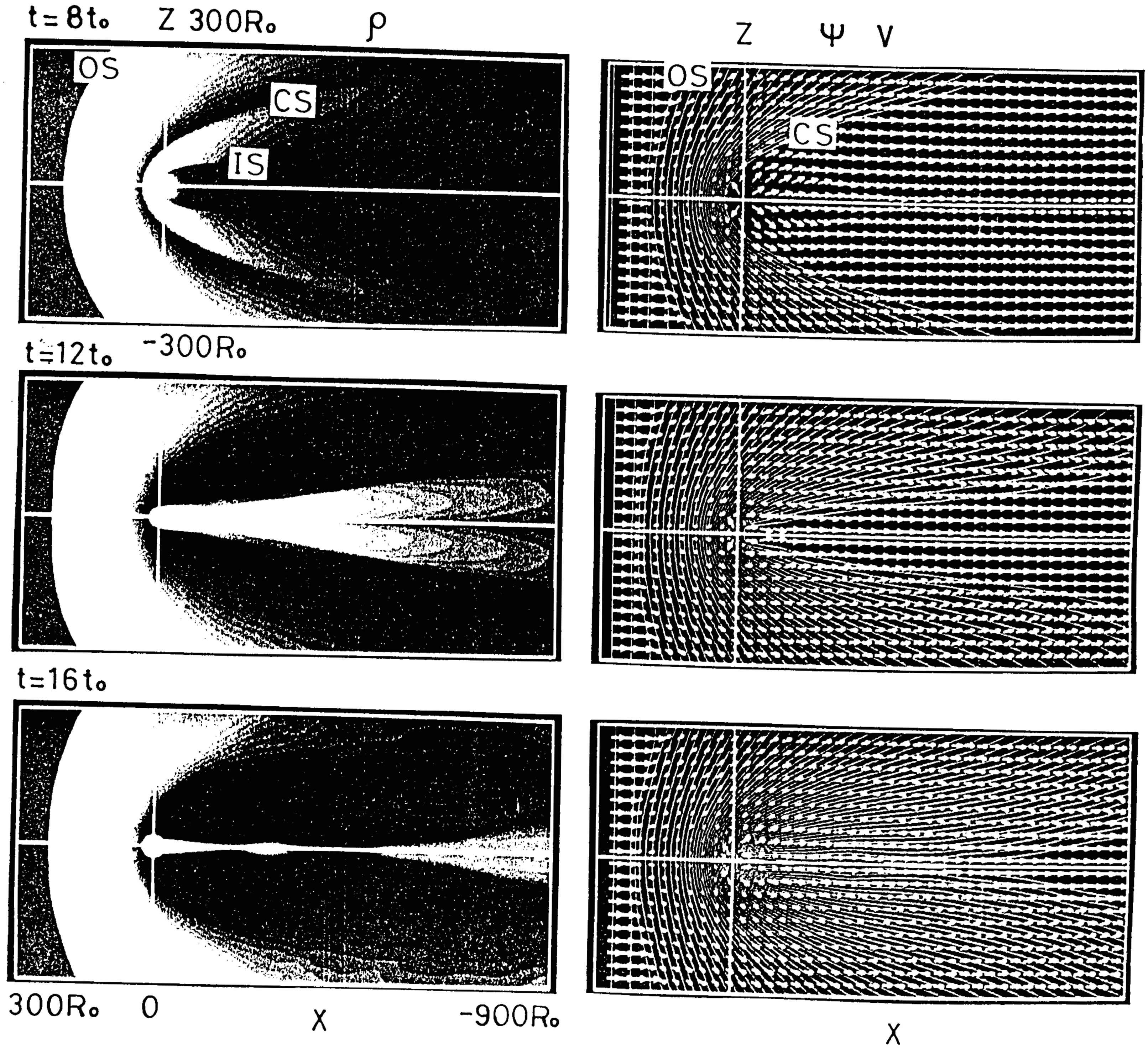
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