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Final Report on NASA Grant NAG5-10282
"Magnetohydrodynamic Modeling of the Jovian Magnetosphere"

1. Introduction

Under this grant we have undertaken a series of magnetohydrodynamic (MHD) simulation and data analysis studies to help better understand the configuration and dynamics of Jupiter's magnetosphere. We approached our studies of Jupiter's magnetosphere in two ways. First we carried out a number of studies using our existing MHD code. We carried out simulation studies of Jupiter's magnetospheric boundaries and their dependence on solar wind parameters, we studied the current systems which give the Jovian magnetosphere its unique configuration and we modeled the dynamics of Jupiter's magnetosphere following a northward turning of the interplanetary magnetic field (IMF). Second we worked to develop a new simulation code for studies of outer planet magnetospheres.

2. The Location and Shapes of Jupiter's Bow Shock and Magnetopause

We have studied the shape and location of the Jovian bow shock and magnetopause by using a combination of magnetic field observations and the global MHD simulations. MHD simulations in which the IMF was set to zero were used to define the boundary shapes and positions and how they depend on solar wind dynamic pressure. In *Joy et al.* [2002] we used polynomial fits to the simulated boundaries along with spacecraft observations to determine the probability of a given position being outside of the bow shock or inside of the magnetopause. The magnetopause and possibly the bow shock have two preferred locations, one representing a compressed magnetosphere and the other an expanded magnetosphere. Variations in the solar wind parameters near Jupiter also show a bimodal distribution but the changes in the solar wind dynamic pressure are not sufficient to account for the observed bimodal distribution of magnetopause positions. Internal pressure changes at Jupiter are required.

In a related study we used additional simulations to argue that the IMF also influences location and shape of the boundaries [*Walker et al.*, 2005]. In simulations without an IMF the equatorial current sheet with its hot plasma forces the magnetopause further from Jupiter at the equator than at the poles. This is called "polar flattening". When the IMF is in the B_y direction or northward magnetopause reconnection acts to reduce polar flattening. For strong northward IMF the magnetosphere changes shape and the magnetopause is found further from Jupiter at the poles. Higher internal plasma pressure at dusk leads to a dawn-dusk asymmetry in the magnetopause position in which the boundary is further from Jupiter on the dusk side. For all of the simulations the ratio of the bow shock stand-off distance to that of the magnetopause was less than that found at the Earth's magnetopause.

3. Currents in the Jovian Magnetosphere

A thin equatorial current sheet with currents flowing around Jupiter dominates Jupiter's middle magnetosphere. In *Walker and Ogino* [2003] we used our simulation code to investigate the structure of the currents in Jupiter's middle magnetosphere and

their connection to Jupiter's auroral zone. However, in our simulations this current is not uniform in azimuth. It is weaker on the day side than the night side with local regions where the current density decreases by more than 50%. In addition to this ring current the current sheet contains strong radial currents. When these radial currents are directed away from Jupiter, they frequently are called "co-rotation enforcement" currents. Outward radial currents are found at most local times but there are regions with currents directed toward Jupiter. The current pattern is especially complex in the local afternoon and evening regions where the current sheet becomes much thicker than in the morning region. In the near equatorial magnetosphere the field-aligned current pattern also is complex. There are regions with currents both toward and away from Jupiter's ionosphere. However, when we mapped the currents from the inner boundary of the simulation to the ionosphere we found a pattern more like that required for the ionosphere to drive corotation with currents away from Jupiter at lower latitudes and currents toward Jupiter at higher latitudes. Since upward field-aligned currents are associated with aurora at the Earth they may be associated with aurora at Jupiter. The upward field-aligned currents map to larger distances on the night side ($40R_J$ to $60R_J$) than on the day side ($20R_J$ to $30R_J$). In the simulations changing the solar wind dynamic pressure did not make major changes in the current sheet or field-aligned currents. The interplanetary magnetic field had a stronger effect on the currents with the strongest currents for northward IMF. However, it took a very long time (>30 hours) for the middle magnetosphere to respond to changes in the IMF.

4. Magnetospheric Dynamics for Northward IMF

In the studies discussed above we limited our analysis to cases in which the Jovian magnetosphere had reached quasi-steady configurations. In *Fukazawa et al.*, [2005] we simulated the Jovian magnetosphere for northward IMF starting from a steady state for southward IMF. We then examined the response of the magnetosphere as a function of time. About 46 hours after the northward IMF reached the dayside magnetopause reconnection started in the Jovian magnetotail and a plasmoid (magnetic O-region) was launched tailward. This was followed by the formation and ejection of three more plasmoids. In each case the reconnection line (X-line) moved tailward with the plasmoid. Magnetic flux tubes from the X-line moved toward and around Jupiter ending up back in the plasma sheet where they were available for additional reconnection. A new reconnection line formed, a plasmoid was ejected and the process repeated. These phenomena occurred with an average period of 34.3 hours.

5. Development of a New Simulation Code for Planetary Studies

Our co-investigators at Science Applications International Corporation worked on developing a new simulation code for use in studying planetary magnetospheres. Our plan was to adapt a semi-implicit code used for investigating solar physics for use in planetary studies. The biggest test of this new code is modeling Jupiter's magnetosphere. This is a very difficult task. A major source of plasma for Jupiter's magnetosphere is the Io plasma torus. The time step for advancing explicit simulation codes like the one used for the studies outlined in sections 2-4 is inversely proportional to the Alfvén velocity near the planet. Unfortunately Io lies very close to Jupiter (~$6R_J$) and in the inner magnetosphere the time step goes approximately as one over the speed of light near

Jupiter. This is a prohibitively small number. (In the simulations in sections 2-4 we modeled the inner magnetosphere of Jupiter by using boundary conditions at $15R_J$ distance rather than actually simulating the inner magnetosphere region.) In principle the semi-implicit code will allow us to use larger time steps and thereby include the inner magnetosphere self-consistently in the simulations. The first step in our effort was to port the code to work on parallel computers. This took a lot of work but was successful. The Jupiter problem is further complicated because much of Jupiter's magnetosphere is rapidly rotating. The new simulation code uses a non-uniform spherical grid system. This is very useful because it allows us to use a dense grid near Jupiter. However the spherical grid also provided us with a problem. Because we had both a rotating system and a solar wind it wasn't clear how to place pole of the spherical grid. Should we place it along the solar wind flow or perpendicular to the solar wind flow? Placing the pole perpendicular to the solar wind makes it difficult to handle the upstream boundary so we placed it along the flow direction. Unfortunately this lead to a serious problem since at the position where the discontinuity of the Jovian bow shock crosses the simulation grid pole the code becomes unstable. We have not yet solved this problem and have not been able to use the new code to model Jupiter. However, a version of the code is working and we have successfully used it to model the interaction of the Jovian wind (corotating Jovian plasmas) with the moon Ganymede. This is possible because no bow shock is formed in this calculation.

6. Publications in Refereed Journals

a. Fukazawa, K., T. Ogino and R. J. Walker, Dynamics of the Jovian magnetosphere for northward interplanetary magnetic field (IMF), *Geophys. Res. Lett., 32*, L03202, doi:10.1029/2004GL021392, 2005.

b. Joy, S. P., M. G. Kivelson, R. J. Walker, K. K. Khurana, C. T. Russell and T. Ogino, Probalilistic models of the Jovian magnetopause and bow shock locations, *J. Geophys. Res., 107*, A10, 1309, doi:1029/2001JA009146, 2002.

c. Walker, R. J., and T. Ogino, A simulation study of currents in the Jovian magnetosphere, *Planet. Space Sci., 51*, 295, 2003.

d. Walker, R. J., S. P. Joy, M. G. Kivelson, K. Khurana, T. Ogino, and K. Fukazawa, The locations and shapes of Jupiter's bow shock and magnetopause, *Physics of Collisionless Shocks* (in press), AIP Press, 2005.