Magnetohydrodynamic Simulations of the Magnetopauses of Saturn, Jupiter and the Earth

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Abstract

We use global magnetohydrodynamic simulations to compare the responses of Saturn, Jupiter and the Earth to the solar wind. We investigate the magnetospheric boundaries in the presence of dayside reconnection and also find waves on the boundary that are consistent with the Kelvin-Helmholtz (K-H) instability. At the Earth and Jupiter reconnection erodes the dayside magnetopause but there is little erosion at Saturn. The waves at Earth are caused by solar wind velocity shear. At Saturn the solar wind velocity shear combines with rotating Kronian plasma to create the waves. At Jupiter the boundary is unstable because of rotating Jovian flows.

1. Introduction

It has long been realized that reconnection can occur at the low latitude magnetopause when the interplanetary magnetic field is directed southward and therefore opposite to that of the Earth. Reconnection drives flows throughout the Earth's magnetosphere. Similarly we would expect reconnection to occur at the large outer-planet magnetopauses at Jupiter and Saturn when the IMF is northward. However at the rapidly rotating giant planets atmospherically driven corotation is the dominant source of convection. Rotating flows extend from the planets to the dayside magnetopauses. In the presence of velocity shear the Kelvin-Helmholtz instability also can occur at the magnetopauses. The Kelvin-Helmholtz instability occurs because of the free energy supplied by the velocity shear. In this paper we investigate the processes that occur at the dayside magnetopauses of the Earth, Jupiter and Saturn by use of global magnetohydrodynamic simulations of the solar wind magnetosphere interaction. In this paper we limit the results to cases with a reconnecting IMF. In section 2 we outline the results for the Earth, Saturn and Jupiter. Finally in section 3 we compare the results from the three planets.

2. Simulations Results

The simulation code used for this study is based on one developed for Earth by [1]. It subsequently has been adapted for studies of Jupiter [2, 3] and Saturn [4, 5].

2.1 The Earth's Magnetopause

Flows in the Earth's magnetosphere are primarily driven by reconnection between the solar wind when it has a southward component and the Earth's magnetic field. However surface waves on the magnetopause can also affect magnetospheric transport. For instance if there is velocity shear between the plasma flowing in the magnetosheath and that flowing in the magnetosphere the kinetic energy of this velocity shear can provide free energy to drive the Kelvin-Helmholtz instability. Velocity shear therefore can influence the transport of energy between the solar wind and the magnetosphere. Instability occurs when the velocity shear reaches a critical speed that allows it to overcome the restoring force of magnetic tension. The K-H instability has been studied extensively at the Earth by using theory, simulations and observations. In particular most simulations have been carried out for low magnetic shear cases (northward IMF) when there is no reconnection at the dayside magnetopause. However recently [6] have presented a detailed study of K-H waves at a reconnecting magnetopause. In this study we have repeated some of their analysis in order to compare the results with our studies of K-H waves for reconnecting configurations at the outer planets.

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In Figure 1 we have plotted the electric field magnitude from a simulation of the interaction between the solar wind and the Earth's magnetosphere. This snapshot was taken 50 m after the IMF was turned from northward to southward. The figure is a plane just 0.25 R_E above the equator. We have superimposed flow vectors on top of the electric field spectrogram. The solid white line is a contour of $B_Z = 0$ and the dashed lines is a contour of $V_X=0$. These give a good approximation of the magnetopause boundary and the inner edge of the low latitude boundary layer (LLBL) respectively. The shading shows that there are two unstable K-H modes one outside of the magnetopause and one inside of the LLBL as suggested by [7]. Thus our study shows that K-H waves can form on the dayside magnetopause of the Earth. The wave vectors (k) are related to the thickness of the magnetopause layer (d) by kd~1. These results are very similar to those found earlier by [6]. The K-H waves propagate along both the dawn and dusk magnetopauses in a simulation with dawn-dusk symmetry. The shear that forms the waves results almost completely from the magnetosheath flow although there is a small contribution from flow returning from reconnection in the magnetotail.

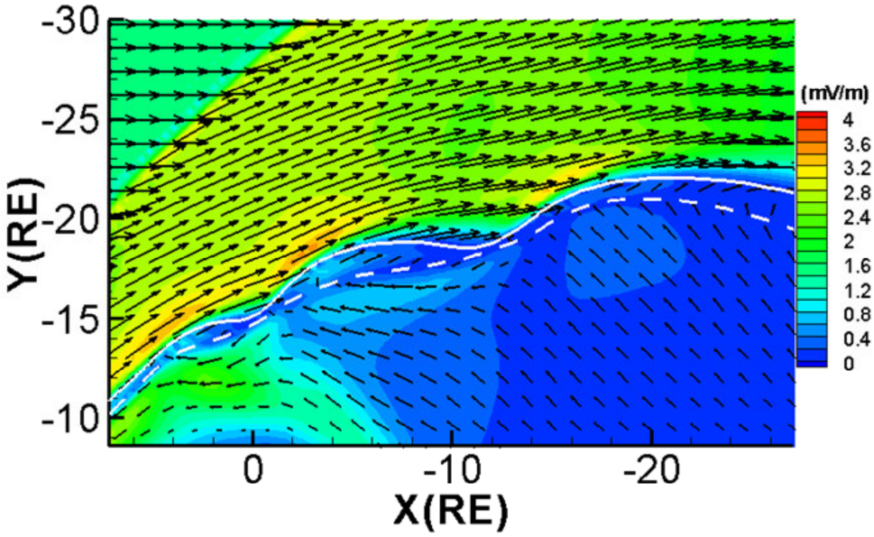

Figure 1. The electric field 0.25 R_E above the equatorial plane in mV/m with flow vectors superimposed. The solid white line is a contour of $B_Z=0$ and approximates the magnetopause while the dashed white line is a contour of $V_X=0$ and approximates the inner edge of the boundary layer. These results are from 50 m after a southward from northward turning of the IMF. The solar wind velocity was 300km/s, $B_Z=-5$nT, n=$5X10^6$ m^{-3} and T= $2X10^5$K.

2.2 Saturn's Magnetopause

We have carried out a series of simulations of the interaction between the solar wind and Saturn's magnetosphere [5]. Saturn differs from the Earth in two ways. First the dominant flow in much of the magnetosphere is caused by atmospherically driven co-rotation and second the main source of plasma is the icy moon Enceladus. In our simulation studies we have investigated the influence of the IMF, solar wind velocity and Enceladus source strength on the physics of the boundary. At Saturn dayside reconnection occurs for a northward component of the IMF since Saturn's internal magnetic field is opposite to that at Earth. For northward IMF vortices form along Saturn's dawn side magnetopause when there is high velocity shear and the condition for the generation of Kelvin-Helmholtz waves is met. We have carried out an analysis similar to that in Figure 1 for Saturn. As at Earth the wave vectors and thickness of the boundary layer are related by kd~1. The waves at this time are linear however as time increases they develop into non-linear K-H vortices. The main difference at Saturn is that rotating flows are important for making the boundary unstable. The waves propagate tailward past dawn. Perhaps the most surprising aspect of the waves at Saturn is that they form for northward IMF but not southward IMF. For northward IMF there is little erosion of the dayside magnetopause, the main effect of reconnection on the dayside is to enhance the electric field on the dawn side so that rotating flows near the magnetopause are enhanced. This leads to instability. About 20 h after a northward IMF interacts with the dayside magnetopause reconnection occurs in the tail. Flows from the tail to the dayside reduce the plasma density in the dayside magnetosphere causing the boundary to become stable. Later in the simulations K-H waves can form on the afternoon magnetopause near dusk. These are related to return flows from night-side reconnection.

2.3 Jupiter's Magnetopause

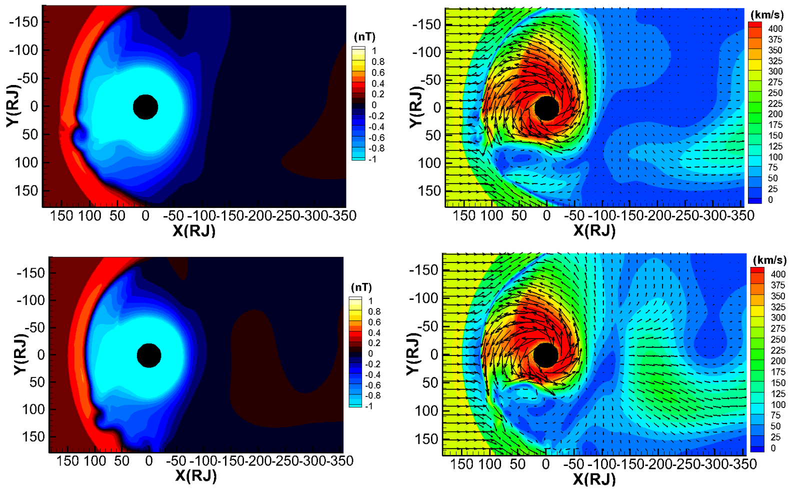

Figure 2 The B_Z component of the magnetic field $0.75R_J$ above the equatorial plane (left) and the velocity magnitude and vectors (right). The top snapshots were taken 28.05 h after a northward IMF of 0.105 nT entered the simulation box while those in the bottom panel were taken at 37.39 h. For this simulation the V_X=300 km/s, n=8X10^4 m^{-3} and T = 2X10^5 K. The source at Io was set to 6.8X10^{30} AMU/s.

Jupiter's magnetosphere like Saturn's is dominated by rotating flows driven by a torque on the atmosphere. The main source of plasma in Jupiter's magnetosphere is ultimately from neutrals whose source is a moon. However in Jupiter's case this is the volcanic moon Io. Heavy ions from Io (oxygen and sulfur) are the main ions. Like Saturn reconnection occurs at Saturn's magnetopause for northward IMF. In Figure 3 we have plotted the north-south component of the magnetic field in the left hand column and the flow vectors and magnitude in the right hand column. These two snapshots were taking 28.05 h and 34.28 h after the northward turning of the IMF. The white line again shows B_Z=0. These waves started at about 18.7 h on the pre-noon magnetopause just like at Saturn. However at Jupiter the waves propagate tailward along the dusk magnetopause rather than the dawn magnetopause. This occurs because the shear at Jupiter is primarily due to rotating Jovian flows rather than the solar wind and since the rotating flow goes counterclockwise toward dusk so do the waves. In the simulations reconnection occurred 80 R_J to 120 R_j down the tail with periods between 34 h and 100 h [3]. The onset of K-H waves occurs when flux tubes from the tail drift around to the dayside and increase the rotational velocity near the late morning magnetopause.

3. Comparative Magnetopause Interactions

. A large number of studies have demonstrated that reconnection is the prime driver of transport in the Earth's magnetosphere. These results are confirmed by the simulations. However we also find Kelvin-Helmholtz waves at the magnetopause. They occur for both low and high magnetic shear. At the Earth our simulations are consistent with the idea that the solar wind provides the velocity shear that in turn provides the free energy source of the waves. In simulations of the Earth's magnetopause K-H waves have been reported for both northward and southward IMF. The situation at Jupiter and Saturn is very different. At Saturn reconnection is less important than at the Earth. Atmospherically driven co-rotation is dominant in much of the Saturn's magnetosphere and K-H waves form initially in the late morning and both the solar wind and Saturn's rotating flows contribute to the shear. The dawn side waves at Saturn propagate tailward along the dawn magnetopause. Our simulations indicate that reconnection is more important for driving flows at Jupiter than at Saturn [4 and references therein] but less important than at Earth. Atmospherically driven rotation is dominant in much of Jupiter's magnetosphere as it is at Saturn. K-H waves also form at Jupiter in the late morning. However they propagate tailward around the dusk side rather than the dawn side. This occuirs because Jupiter's rotating flows provide the shear necessary for the K-H waves. There is a big difference in the scale of the waves at the three planets. The wave lengths at the Earth are about 10 $R_{E.}$ At Saturn they are 10 R_S – 20 R_S and at Jupiter they are about 60 R_J. Not surprisingly the wave lengths scale with the size of the magnetosphere. The scale of the magnetosphere in turn determines the size of the boundary layer where the waves form.

4. Acknowledgments

RJW would like to thank Katherine Ramer, Todd King and Bill Harris for help with analysis software and processing the simulation results. The work was supported by NASA grants NASA NNX09AQ54Q. KF was supported by Grant-in Aid for JSPS Fellows No. 09J01416. Computing support was provided by the Information Technology Center, Nagoya University, the Solar-Terrestrial Environment Laboratory, Nagoya University as a computational joint research program and by the National Institute of Information and Communications Technology This study was also carried out as a program of Joint Usage / Research Center for Interdisciplinary Large-Scale Information Infrastructures including the Information Technology Center, the University of Tokyo and the Research Institute for Information Technology, Kyushu University.

7. References

1. T. Ogino, R. J. Walker and M. Ashour-Abdalla, A global magnetohydrodynamic simulation of the response of the magnetosphere to a northward turning of the interplanetary magnetic field, *J. Geophys. Res.*, 99, 1994, 11027 - 11042.

2. T. Ogino, R. J. Walker and M. G. Kivelson, A global magnetohydrodynamic simulation of the Jovian magnetosphere *J. Geophys. Res.*, *103,* 1998, 225-235.

3. K. Fukazawa, T. Ogino, and R. J. Walker, A simulation study of the dynamics in the distant Jovian magnetotail, *J. Geophys. Res*., *115*, 2010, A09219.

4. K. Fukazawa, S. Ogi, T. Ogino, and R. J. Walker, Magnetospheric convection at Saturn as a function of IMF B_Z, *Geophys. Res. Lett., 34*, 2007, L23210.

5. Walker, R. J., K. Fukazawa, T. Ogino, and D. Morozoff, A simulation study of Kelvin-Helmholtz waves at Saturn's magnetopause, *J. Geophys. Res., 116*, 2011, in press.

6. S. G. Claudpierre, S. R. Elkington, and M. Wiltberger, Solar wind driving of magnetospheric ULF waves: Pulsations driven by velocity shear at the magnetopause, J. *Geophys. Res., 113*, 2008, A05218.

7. Z. Y. Pu, and M. G. Kivelson, Kelvin-Helmholtz waves at the magnetopause: Solutions for compressible plasmas, *J. Geophys. Res., 88*, 1983, 841 – 852.