The magnetospheres of Jupiter and Saturn and their lessons for the Earth

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Abstract

The study of planetary magnetospheres allows us to understand processes occurring in the Earth’s magnetosphere by showing us how these processes respond under different conditions. We illustrate lessons learned about the control of the size of the magnetosphere by the dynamic pressure of the solar wind; how cold plasma is lost from magnetospheres; how free energy is generated to produce ion cyclotron waves; the role of fast neutrals in a planetary magnetosphere; the interchange instability; and reconnection in a magnetodisk. Not all information flow is from Jupiter and Saturn to Earth; some flows the other way.

Keywords: Jupiter; Saturn; Earth magnetosphere

1. Introduction

In the laboratory we can modify the conditions under which we control our experiments to test our hypotheses on how processes behave, but in the Earth’s magnetosphere we have only a narrow range of conditions imposed by uncontrollable variations in the solar wind. Many possible factors such as the rotation rate of the Earth or the magnetic moment cannot be changed. Thus the opportunity to explore the magnetospheres of other planets is a welcome chance to gain a deeper understanding of terrestrial processes by exploring them in ranges of parameter space well beyond the terrestrial norm. In this review we examine lessons learned at Jupiter and Saturn in the areas of control of the size of the magnetosphere by the solar wind dynamic pressure, the circulation of plasma, the generation of ion cyclotron waves, the production and importance of fast neutrals, the interchange instability, and reconnection.

2. Control of the size of the magnetosphere

The size of the terrestrial magnetosphere ($R_{mp}$) is generally calculated by the balance of the solar wind dynamic pressure against the pressure exerted by the magnetic moment of the Earth

$$R_{mp} \propto M^{1/3} (\rho u^2)^{-1/6}$$

(1)

where $M$ is the magnetic moment of the Earth, $\rho$ is the density, and $u$ is the bulk velocity of the solar wind. There is no adjustment for internal conditions. Fig. 1a and b shows a plot of the empirically determined relationship between the magnetopause nose position and the solar wind dynamic pressure for Jupiter and Saturn. Here the relationship does not depend on solely the magnetic pressure gradient of the dipole, i.e., an inverse one-sixth power law, but a $-1/4.4$ power law (Huddleston et al., 1998a; Arridge et al., 2006). The reason for the difference is that in both magnetospheres there are sources of cold plasma that are spun up by the rotating magnetosphere stretching out the magnetic field and reducing the gradient in the total pressure. In a vacuum there is force balance between the
magnetic gradient force and the curvature force that sets the one-sixth power law but in a plasma, especially one that rotates quickly, the pressure balance is achieved with a weaker gradient. While the Earth possesses neither a mass source deep in the equatorial region of the magnetosphere nor a fast rotation, it does have geomagnetic storms that do relax the pressure gradient. Thus at times the size dependence of the Earth’s magnetosphere on the solar wind dynamic pressure will be different than the norm.

3. Circulation of magnetospheric plasma

Both Jupiter and Earth have strongly convecting cold plasma populations as sketched in Fig. 2a and b. The jovian plasma, mainly provided by Io, is spun up to near corotation velocities by the rapidly rotating planet’s ionosphere (see Russell, 2001 and references therein). The magnetosphere has to dispose of this plasma or else the magnetosphere will continually be more and more stretched. It is thought to do this by forming an island in the tail laden with ions coming from Io (Vasyliunas, 1983). The Earth on the other hand dumps its cold plasma on the dayside when the solar wind erodes the dayside magnetosphere (Kavanagh et al., 1968). Does Jupiter (or Saturn) lose plasma in this manner also? We do not know at present as we have had limited studies of cold plasma at these boundaries.

4. Ion cyclotron wave generation

Ion cyclotron waves arise at Io when the SO$_2$, SO, and S in the Io exosphere are ionized. A set of dynamic spectra covering five Galileo flybys are shown in Fig. 3a (Russell et al., 2003). These waves are produced just below the cyclotron frequency of the ion when the pick-up process produces a cold ring beam in velocity space (e.g., Huddleston et al., 1998b). Fig. 3b shows a similar process occur-
The ion cyclotron waves shown in Fig. 3a and b extend far from the bodies producing the gases that become ionized but it is impossible for ions to cross magnetic field lines in a collisionless plasma and impossible for them to retain their free energy in an ordinary collisional regime. The transport to these distances must be through fast neutrals, accelerated initially as ions but neutralized and shot across the field lines only to be ionized again far from the source. The mechanism for such an acceleration and transport model has been discussed by Wang et al. (2001) and is shown in Fig. 4. When a cold exospheric neutral becomes ionized it is accelerated in the corotation electric field. At
this point it begins to gyrate and drift along the curved cycloidal paths shown. At some point it will become neutralized, if it remains in the exosphere, and then it will follow a straight line trajectory to some distant point. To the extent that the field line at the reionization location has the same orientation as at the initial acceleration location, this

Fig. 3. Dynamic spectra of the magnetic oscillations associated with ion cyclotron waves produced in rapidly rotating planetary magnetospheres: (a) Jupiter’s sulfur dioxide, sulfur monoxide, and sulfur waves near Io (Russell et al., 2003), (b) Saturn’s water group ion cyclotron waves in the E-ring torus region (Russell et al., 2006). The white curves in (a) are the local gyro frequencies of singly charged sulfur, sulfur monoxide, and sulfur dioxide. The ion cyclotron waves in the Saturnian magnetosphere follow the singly ionized water group gyro frequency.
process represents merely the translation of the free energy to a new location. The message for Earth is clear. Fast neutrals have long been thought to provide strong diagnostics of magnetospheric processes, and they have been invoked as a loss mechanism for energetic trapped ions, but in fact their importance may be much more than that. They may be agents of mass transfer across field lines and not just have local effects.

6. Interchange instability

At the outer edge of the Io torus there is a region of turbulent flux tubes where the plasma energy content of the tubes is quite variable. This variable energy content will change the strength of the magnetic field within the tubes that are in total pressure equilibrium with their neighbors. These flux tubes are rooted in the ionosphere that helps

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**Fig. 4.** Mechanism for creating an exodisk of fast neutrals, providing a sheet of particles that ionize at some distance from Io after an initial ionization, followed by neutralization. The final ionization releases free energy for the generation of the ion cyclotron waves (Wang et al., 2001).

**Fig. 5.** Linearly detrended data showing apparent interchange between different flux tubes. (Left) Jupiter: at edge of Io torus; (Right) Saturn: at edge of quiet E-ring torus.
Fig. 6. Detrended magnetic field showing flux tubes that appear to be moving inward in denser plasma that is moving outward. (a) Jupiter in Io torus where increased field strength signals less dense plasma (Russell et al., 2000). (b) Saturn, in quiet E-ring torus where inward moving flux tubes have more thermal energy density than the surrounding plasma (Leisner et al., 2005). The direction $b$ is along the field; $c$ is in the direction of corotation; and $a$ is in the direction that makes the $abc$ coordinate system orthogonal.

Fig. 7. Structure of the magnetodisk current sheet showing the onset of tearing islands. The neutral points grow slowly as the dense magnetodisk plasma moves outward (Russell et al., 1999). Here $a$ is the direction in which the change in magnetic field across the sheet points; $b$ is the normal to the sheet; and $c$ is in the direction the average current flows.
control their motion, but the dynamical control in the equator may be different, so the field lines bend and the components of the magnetic field will differ in each tube. This region of turbulent convection is shown here for both Jupiter (left) and Saturn (right) in Fig. 5. The location of this region may signal where the coupling of the ionosphere and magnetosphere changes. For example, it could be the location where corotation stops and subcorotation begins, thus marking a region of velocity shear. Similarly at Saturn near about 6 $R_S$ in the E-ring torus there is often a similar change in character in which there is different plasma pressure in adjacent flux tubes. Perhaps this is a velocity shear zone too. While these observations certainly have implications for each other, they also suggest that on Earth we should be careful to examine velocity shears internal to the magnetosphere as triggers for interchange signatures and the radial mixing of plasmas of different origins.

Interior to the Io torus and also interior to the E-ring torus we see the flux tubes shown in Fig. 6a and b. These tubes appear to be moving inward in both magnetospheres but have very different appearances. In the Saturn magnetospheres these moving tubes have warmed up relative to their neighbors (Leisner et al., 2005) and in the jovian magnetosphere the plasma pressure appears to be reduced (Russell et al., 2000), so that the saturnian tubes have a depression in field strength and the jovian ones an increase. In both magnetospheres the tubes appear to be more empty of plasma than the surrounding plasma. The lesson here for magnetospheres in general is that thin flux tubes are very important for transporting magnetic flux quickly through a flowing plasma much like small bubbles moving through a fluid.

7. Reconnection in a magnetodisk

Neutral points in the magnetic field form in the jovian magnetodisk well inside the point where substorms are seen to be initiated (Russell et al., 1999). Fig. 7 shows a series of plots of magnetodisk crossings at increasing distances. The vertical component $B_\theta$ starts to have nulls around 40 $R_J$ but no dynamics of the magnetosphere occur to about 50 $R_J$ or more (Russell et al., 1999). Thus neutral points can remain

![Diagram](image_url)

**Fig. 8.** Strong rapid reconnection occurring in a rapidly rotating system. (a) Jovian tail, inside reconnection point (Russell et al., 1998). (b) Saturn tail, outside reconnection point. (c) Interpretation of geometry of two separate events, one seen inside the reconnection point and one outside, resulting in southward and northward turnings, respectively. The swept-back nature of the magnetic meridian is shown in the shaded plane. Angular momentum conservation becomes important to the dynamics of the plasma as it is pulled inward or pushed outward rapidly. The two black dots represent the plasma in the plasma sheet that is being swept up by the reconnected magnetic field. Point A corresponds to the observation shown in (a). Point B is a location like that in (b) beyond the reconnection point.
quiescent for long periods without undergoing dynamic change. This is presumably because the Alfvén velocity is small in such regions and reconnection proceeds slowly. This provides a lesson for Earth where reconnection may first appear in the magnetotail plasma sheet well before the poleward expansion of the substorm, which could result from reconnection reaching the more rarefied plasma conditions on tail field lines.

When reconnection does take place, it can be very rapid as illustrated in these two examples from Galileo (Russell et al., 1998) and Cassini in their respective current sheets (Fig. 8a and b). The rapidity of reconnection is demonstrated both by the sudden onset of the north–south component and by the strength that the field reaches as it tries to accelerate the plasma away from the reconnection site. Fig. 8c shows our interpretation of the relative location of these two events in these rapidly rotating magnetospheres. The rapidity and the strength are presumably due to the near vacuum condition in the jovian and saturnian tail lobes, that promote explosive reconnection once

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![Diagram](image-url)

Fig. 9. Near-Earth neutral point model of a substorm showing (top) convection of flux and plasma to the tail with subsequent tail thinning; (middle) formation of near-Earth neutral point and substorm; and (bottom) reconnection reaching the tail lobe and releasing the plasmoid.
the x-point has reconnected the closed flux in the plasma sheet.

We can apply the lesson to Earth in the current substorm paradigm (e.g., Mishin et al., 2001). Fig. 9 shows the sequence of growth phase to expansion phase noon–midnight meridian profiles of the magnetic field during a substorm. After thinning (top panel) due to a southward turning of the IMF, reconnection appears in the near-Earth magnetotail current sheet. Initially it is quiescent, slowly building a plasmoid in the tail. Eventually the reconnection region uses up all of the dense plasma surrounding it and reaches the low density plasma in the lobes. At this point reconnection becomes rapid and the plasmoid is ejected down the tail.

8. Summary and conclusions

This review has illustrated just a few of the situations in which we can learn more about the way magnetospheres work by studying the range of different magnetospheres presented to us by the solar system. Magnetospheres differ in their size, rotation, and mass loading rates. From these differences we have learned how the pressure in the magnetosphere helps control the size of the magnetosphere. We see how the rate of reconnection is modulated in a magnetosphere. We have determined that both mass loading and reconnection lead to plasma circulation. We have learned how ion cyclotron waves are created and what they tell us about the state of the magnetosphere. We see how isolated flux tubes are produced and transported and we have determined the role of fast neutrals in mass transport and loss from planetary magnetospheres.

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