GEOPHYSICAL RESEARCH LETTERS, VOL 17, NO. 10, PAGES 1681-1684, SEPTEMBER 1990

1990-02

Plasma Convection in Neptune's Magnetosphere

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Abstract. The magnetosphere of Neptune changes its magnetic configuration continuously as the planet rotates, leading to a strong modulation of the convection electric field. Even though the corotation speed is considerably larger, the modulation causes the small convection speed to have a cumulative effect, much like the acceleration of particles in a cyclotron. A model calculation shows that plasma on one side of the planet convects out of the magnetosphere in a few planetary rotations, while on the other side it convects slowly planetward. The observation of nitrogen ions from a Triton plasma torus may provide a critical test of the model.

1. Introduction

The dynamics of low-energy plasma in planetary magnetospheres is determined to a large extent by the relative contributions of solar wind driven convection and corotation with the planet. In the Earth's magnetosphere corotation is dominant near the planet, resulting in the high density plasmasphere [Nishida, 1966; Brice, 1967], whereas sunward, solar wind driven convection is dominant further out. The magnetospheres of Jupiter and Saturn are corotation dominated throughout [Brice and Ioannidis, 1970; Siscoe, 1979]. In each of these cases the determining factor is the ratio of the corotation to convection electric fields in an inertial reference frame centered on the planet. The planetary rotation axes are all approximately aligned with the planetary magnetic dipole axes and perpendicular to the direction of the solar wind flow, causing the magnetospheric plasma flow to be quasi-steady in such an inertial reference frame. A different situation occurred at Uranus during the Voyager 2 encounter, when the planetary rotation axis was approximately aligned with the solar wind flow and inclined at a large (~60°) angle to the magnetic dipole axis. Here the magnetospheric plasma flow was quasi-steady in a reference frame which rotates with the planet and in which there is no corotation electric field. Therefore the magnetosphere of Uranus was convection dominated throughout [Hill, 1986; Vasyliunas, 1986; Selesnick and Richardson, 1986; Selesnick, 1987]. If a planetary rotation axis is not approximately aligned with either the magnetic dipole axis or the solar wind flow direction, then there exists no reference frame in which the plasma flow is quasi-steady and estimation of the relative importance of convection and corotation is more difficult. Such is the situation at Neptune.

At the present phase of its orbit about the Sun, Neptune's rotation axis forms an angle of 113° with a vector from the Sun to Neptune which we assume to be in the direction of the solar wind flow (the north pole of Neptune is near the extreme of its excursion away from the Sun direction). The recent results from the Voyager 2 magnetometer have shown that the magnetic dipole axis of Neptune is inclined by ~47° from the rotation axis [Ness *et al.*, 1989]. The combined effect of these two angles is a planetary magnetic field whose orientation relative to the impinging solar wind changes continuously with the rotation of the planet, varying between extreme cases in which the angle between the dipole axis and the solar wind direction is ~20° and ~114° [e.g. Ness *et al.*, 1989; Belcher *et al.*, 1989]. Intermediate values of this angle pass through 90° but not through 0. When the angle is large the instantaneous configuration of the magnetosphere is similar to those of Earth, Jupiter and Saturn; we call such a configuration "Earth-like". When the angle is small there exists a "pole-on" configuration which is unique among the explored planets (although such a configuration will exist at Uranus during certain phases of its orbit). These names refer only to the orientations of the planetary magnetic field relative to the solar wind flow direction. A continuous pole-on configuration has been discussed by Siscoe [1975] (see also Vasyliunas [1986]) with regard to expectations prior to the Voyager 2 encounter with Uranus. However, as described below, that case leads to plasma dynamics considerably different from those of the changing configuration at Neptune. A qualitative understanding of the plasma dynamics in Neptune's magnetosphere can be obtained by relatively simple analysis. However, the question of corotation versus convection cannot be resolved without a model convection electric field. The qualitative picture is described below and a model calculation in the following section.

2. Qualitative description

The magnetic topology that would exist in the noon-midnight meridian, for a northward interplanetary magnetic field (IMF), is sketched in Figure 1*a* for the Earth-like configuration and Figure 1*b* for the pole-on configuration. The directions of the planetary rotation axis, **Ω**, and magnetic dipole axis, **M**, are shown in each case by arrows. It is assumed that magnetic merging (reconnection) occurs between the planetary and interplanetary magnetic fields and drives a convection pattern indicated by the open arrows. The case of northward IMF provides the maximum convection rate in the Earth-like configuration (similar to southward IMF at Earth where **M** has the opposite polarity), but reduced convection with similar directions relative to **M** will occur for all IMF orientations. In the pole-on configuration the convection rate is nearly independent of IMF direction because the geometry of Figure 1*b* will exist in whichever plane the IMF lies.

Paper number 90GL00736
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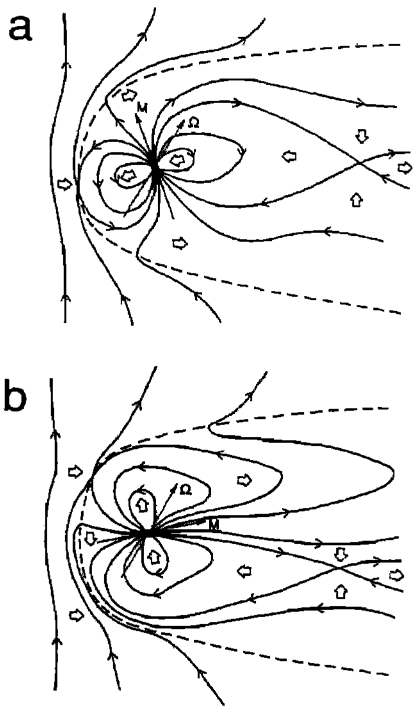

Fig. 1. The "Earth-like" (a) and "pole-on" (b) configurations of Neptune's magnetosphere. The magnetic configuration changes continuously between these two extremes as the planet rotates. The open arrows show plasma convection. **Ω** is the planetary rotation axis and **M** is the magnetic dipole axis.

The efficiency of coupling between the solar wind and the sunward convection in the inner magnetosphere is determined by the length of the merging line across the dayside magnetopause through which open magnetic field lines are connected to the polar cap. For the pole-on configuration the planetary and interplanetary magnetic fields are anti-parallel only in the plane of Figure 1*b*. Therefore the dayside merging line is short and only a small fraction of the total potential drop across the magnetosphere is mapped to the polar cap, providing inefficient coupling to the inner magnetosphere. The anti-parallel merging model of Crooker and Siscoe [1986], which has had success in explaining the decreasing cross-polar potential with dipole tilt for the Earth, predicts that the dayside merging line shrinks to zero for an exactly pole-on magnetosphere, so there would be no convection through the inner magnetosphere in that case. The maximum length of the dayside merging line is obtained near the Earth-like configuration where the dipole and solar wind direction are perpendicular. Then the planetary and interplanetary magnetic fields are anti-parallel across the whole dayside magnetopause.

In the Earth-like configuration, the magnetic field lines which are merged with the IMF at the dayside magnetopause (Figure 1*a*) are at the same magnetic longitudes as the field lines which, in the pole-on configuration, form an X-line in the magnetotail (Figure 1*b*). As the planet rotates there must be a point at which the field lines disconnect from the IMF and, assuming quasi-static fields, the magnetosphere is entirely closed. Even if the steady-state configurations of Figure 1 do not have time to become established, there is a disruption of plasma convection due to merging. Inclusion of this effect is beyond the scope of the model described below and we assume a smooth transition of the coupling efficiency. This assumption should not have a significant effect on the resulting plasma motion.

If the solar wind-magnetosphere coupling is by a viscous interaction rather than by magnetic merging then the direction of plasma convection in the Earth-like configuration is approximately the same as described above. The coupling efficiency to the inner magnetosphere also approaches zero for the exactly pole-on case because the polar cap boundary becomes an equipotential. There are possible configurations where the merging and viscous interactions do not give the same direction for the convection electric field, such as Neptune's pole-on configuration with southward IMF, but the coupling efficiencies are always small. The viscous interaction is probably important for the Earth-like configuration in the case of a purely southward IMF, but the coupling efficiency in this case should still be larger than in the pole-on configuration where merging may always occur but the efficiency is near zero.

Standard scaling arguments [Siscoe, 1979] applied to Neptune show that the velocity of corotation is everywhere larger than that of convection. However, in a corotating plasmasphere the small effects of convection are constant in time and cancel over one complete rotation. At Neptune convection is always fastest in the Earth-like configuration which always occurs when a given element of corotating plasma is at the same local time. Therefore the small convection velocity has a cumulative effect over several planetary rotations, leading to a net transport in the sunward direction. Viewed from the non-rotating reference frame, the plasma executes a spiral motion in the magnetic equator, moving either inward or outward depending on its location at the time of the Earth-like configuration. There is an analogy between this motion and particle acceleration in a cyclotron, where gyrating particles are accelerated by an electric field which is modulated at the gyro-frequency. At Neptune the role of gyration about magnetic field lines is taken by corotation with the planetary magnetic field.

3. Model

A simple model of the convection electric field for application to magnetospheres with arbitrary orientations of the planetary rotation and magnetic dipole axes was given by Selesnick and Richardson [1986]. The electric field is uniform throughout the magnetic equatorial plane and, for a fixed IMF, proportional to $\hat{\mathbf{M}} \times \hat{\mathbf{V}}_{sw}$, where $\hat{\mathbf{M}}$ and $\hat{\mathbf{V}}_{sw}$ are unit vectors in the direction of **M** and the solar wind velocity respectively. The proportionality constant is determined by the solar wind-magnetosphere coupling efficiency for the orientation at which this efficiency is maximum. The variation in the coupling efficiency due to the changing direction of **M** is represented by the vector product. The derivation of this model was based on a mapping of the solar wind electric field from above the magnetic polar regions, which is always valid for a viscous interaction, but from the above discussion we see that it also has the correct behavior for Neptune with a magnetic merging interaction.

The strength of the convection electric field is the coupling efficiency, η, times the solar wind electric field, $V_{sw}B_{sw}$. At the Voyager 2 Neptune encounter the solar wind speed was $V_{sw} \approx 400$ km/s [Belcher *et al.*, 1989] and the solar wind magnetic field (IMF) was $B_{sw} \approx 0.2$ nT [Ness *et al.*, 1989]. These values are consistent with average solar wind conditions. The coupling efficiency at Earth reaches a maximum value of $\eta \approx 0.2$ for southward IMF [Reiff *et al.*, 1981; Paschmann, 1986]. The planetary magnetic field at the magnetopause is proportional to the square root of the solar wind pressure, which, like the IMF magnitude, varies approximately inversely with heliocentric distance. Therefore the ratio of magnetic fields across the magnetopause is, on average, approximately the same for all planets and it is reasonable to expect that η should be also (although observations of a magnetic flux deficit in the outer heliosphere [Winterhalter *et al.*, 1990] may decrease η somewhat). Adopting an average value of $\eta = 0.1$ with the solar wind parameters mentioned above gives a convection electric field at Neptune of $E_c \approx 0.01$ mV/m. In the model this value is modulated by $\hat{\mathbf{M}} \times \hat{\mathbf{V}}_{sw}$. For comparison the corotation electric field, at longitudes where it provides all of the corotation velocity, is $24/L^2$ mV/m.

The magnitude of the convection electric field is plotted versus time in Figure 2. The maximum value is reached twice per Neptune day when M and V_{sw} are perpendicular. The minimum is reached only at the pole-on configuration. Trajectories of cold plasma particles are found by numerically integrating the convection velocity, $\mathbf{V}_c = \mathbf{E}_c \times \mathbf{B}/B^2$, over time. The planetary magnetic field, $\mathbf{B}$, is a simple dipole with moment 0.13 GR_N^3 [Ness *et al.*, 1989] tilted by 47° from the rotation axis. Two such trajectories in the magnetic equatorial plane are shown in Figure 3. They were calculated in the rotating reference frame and then the equatorial plane was rotated at Neptune's 16.1 hour period [Warwick *et al.*, 1989] to include corotation. Both particles were started at $L = 14$ at the time of the Earth-like configuration. The solid and dashed curves are for particles which started at local noon and midnight respectively, and then spiraled outward and inward.

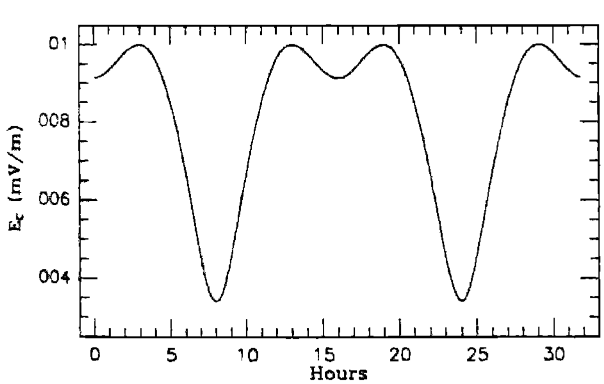

Fig. 2. Model convection electric field versus time for two full planetary rotations starting from the Earth-like configuration. The deep minima occur at the pole-on configuration.

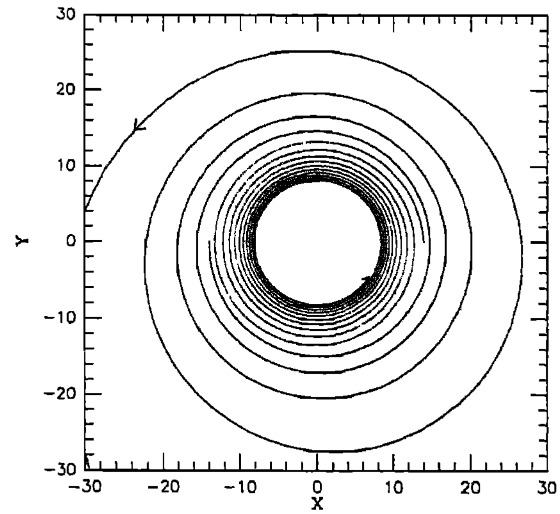

Fig. 3. Two sample plasma trajectories in the magnetic equator showing the cyclotron-like motion. The solid (dashed) curve represents a particle which started during the Earth-like configuration at local noon (midnight) and spiraled outward (inward).

4. Discussion

For the parameters used in the calculations of Figure 3, plasma which is near local noon during the Earth-like configuration escapes from the magnetosphere after a few planetary rotations (~60 hours). The escape time is determined by the pitch of the spiral which in turn depends on the magnitude of the convection electric field. If η is reduced from the above value then the escape time increases by a similar factor. The short escape time also depends on a sufficiently large decrease in the convection electric field at the pole-on configuration, as in Figure 2. Plasma which is near local midnight during the Earth-like configuration convects slowly planetward.

The Voyager 2 plasma experiment detected in Neptune's magnetosphere a tenuous plasma with sharp variations in density [Belcher *et al.*, 1989]. Both the low density and the sharp variations are reminiscent of observations at Uranus [e.g. McNutt *et al.*, 1987], suggesting that the two magnetospheres have similar plasma dynamics. Further evidence of convective transport at Neptune may be available from the probable detection of nitrogen (N^+) ions. If the N^+ derive from a Triton plasma torus [Delitsky *et al.*, 1989] then they can provide a tracer for particle trajectories. Some sample trajectories deriving from a hypothetical torus at $L = 14$ are shown in Figure 4. The reference frame now rotates with the planet and the calculations were again started at the Earth-like configuration, at which time the negative X-axis pointed toward the Sun. The dashed circle is the location of the torus and the solid curves with arrows are the Voyager 2 (V2) location projected along dipole

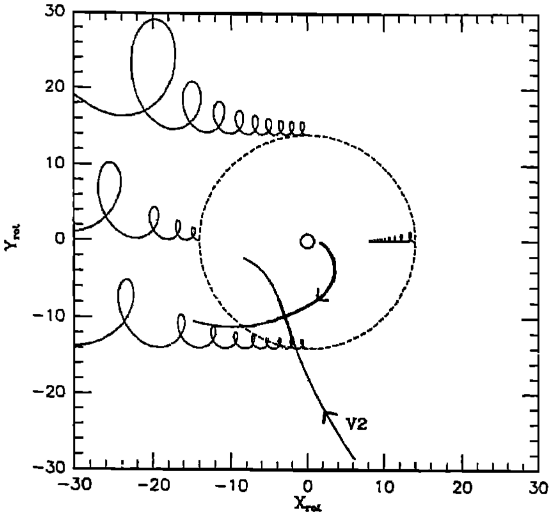

Fig. 4. Plasma trajectories in a coordinate system rotating with Neptune. The dashed circle, where the trajectories begin, represents a hypothetical Triton plasma torus. The solid curves with arrows are the Voyager 2 (V2) position projected along dipole magnetic field lines, with the heavier portions locating regions of higher observed plasma density.

magnetic field lines. The spacecraft is shown only in regions where the offset-tilted-dipole model of Ness *et al.* [1989] is thought to be valid (see also Stone *et al.* [1989]). The heavier portions of the V2 trajectory represent regions where higher plasma densities were observed, although there were also density variations within these regions. According to the model, plasma from the Triton torus should be observed primarily inside the torus for positive X in Figure 4 and outside for negative X. That no plasma was observed inside the torus near the negative X-axis and that the highest densities were observed near the positive X-axis may support this model. Future analysis to determine the source location of the plasma, and in particular a detection of N^+ outside the torus for negative X, will help to evaluate the role of convection in Neptune's magnetosphere.

Acknowledgements. The author thanks E. C. Stone and J. D. Richardson for helpful discussions. This work was supported by NASA under contracts NAS7-918 and NGR 05-002-160.

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(Received: February 16, 1990;
accepted: March 19, 1990.)