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The Magnetosphere of Saturn

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Abstract

This talk will summarize our present understanding of the global configuration of Saturn's magnetosphere. This configuration is the result of a complex, non-linear interplay between solar wind interaction, fast rotation of a magnetized planet, and significant plasma sources inside the magnetosphere. Saturn's magnetosphere is dominated by water group molecules and ions originating from Enceladus, the other icy satellites and the spectacular rings of Saturn. Properties of Saturn's magnetospheric plasma, magnetic field and radio emissions vary at a ~10.7 hour period, close to the period of planetary rotation with drifts of ~1% per year. Identifying the source of the periodicity has proved challenging. We will discuss the possibility of an atmospheric source of the observed periodicities.

1. Introduction

Saturn has a dipole-like intrinsic magnetic field with the dipole axis closely aligned with the axis of planetary rotation. The equatorial magnetic field ($B_S \approx 2\times10^{-5}$ T) is very close to the equatorial magnetic field of Earth ($B_E \approx 3\times10^{-5}$ T) and about an order of magnitude smaller than that of Jupiter ($B_J \approx 4\times10^{-4}$ T). The equatorial radius of Saturn ($R_S \approx 6.0\times10^{4}$ km) is comparable to the radius of Jupiter ($R_J \approx 7.0\times10^{4}$ km) and is about an order of magnitude larger that the radius of Earth ($R_E \approx 6.4\times10^{3}$ km). The rotation periods for Jupiter ($T_J \approx 10$h) and Saturn ($T_S \approx 10.5$h) are quite close, and they rotate about 2.5 times faster than Earth ($T_E \approx 24$h). Centrifugal accelerations at the planetary equator, consequently, are comparable at Jupiter and Saturn, and they exceed that of Earth by about 1.5 orders of magnitude.

2. Plasma Sources

One of the fundamental questions of magnetospheric physics is the sources of the plasma that populates a magnetosphere. At Earth, many years of observational and theoretical work have demonstrated that there are two significant sources: the solar wind and the Earth's upper atmosphere. The mechanisms for entry and the relative importance of each source is still hotly debated, but there are no additional contenders of any significance. At Saturn, by contrast, there is a rich set of possible plasma sources: the solar wind, Saturn's ionosphere, Titan, the rings, and the icy satellites. The dominant compositional signature (H^+, H_2^+, and water group ions) points directly to water ice on rings and satellites as the primary source. Observations from a close Cassini flyby revealed the surprising fact that Enceladus is actively venting gas and ice grains [1-5]. The primary gas emitted is water vapor, potentially accounting for the observed vast cloud of water vapor and water products.

3. Transport

The rings, Enceladus and the icy satellites produce ~10^2 kg of water group ions per second near the equator. This plasma is "loaded" to rotating closed magnetic field lines that are increasingly stretched by the balance between magnetic stresses and centripetal forces. In the MHD limit the ionosphere rotates with the planet and it drags along closed magnetic field lines that are increasingly mass loaded in the equatorial region. The magnetic field lines are increasingly stretched as more and more plasma is added. The increasing plasma content requires the transfer of more and more momentum from the rotating ionosphere to the increasingly stretched field line. However, the finite ionospheric conductivity limits this momentum transfer, and consequently, the angular velocity of the heavy'equatorial part of the magnetic field line exhibits an increasing corotation lag. Finally, the field line becomes so heavy that the ionosphere is unable to drag it around any more and corotation ``breaks down" near a radial distance of ~15 R_S. When a mass-loaded heavy magnetic flux tube stretches beyond the corotation breakdown the plasma will continue moving outward unless there is some process that inhibits this motion. On the dayside the magnetopause acts a barrier and forces the magnetic field line to move along the inner boundary of the magnetosphere thus forcing a corotation-like motion around the planet. On the nightside, however, the plasma can move without much resistance into the low pressure magnetotail. The magnetic field lines remain attached to the corotating ionosphere at one end and to the outward moving heavy equatorial plasma on the other end. Eventually the field line becomes so stretched and thin that a closed magnetic loop is created that can now freely move down the magnetotail. On the planetary side the newly shortened field line is "shed" of its plasma content, and the magnetic stress pulls the equatorial part of the field line towards the planet, restoring the flow toward corotation. This process is called the "Vasyliunas cycle" [6].

4. Periodicities

Properties of Saturn's magnetospheric plasma, magnetic field and radio emissions vary at a ~10.7 hour period, close to the period of planetary rotation with drifts of ~1% per year [7-9]. Identifying the source of the periodicity has proved challenging. Drivers internal to Saturn are inconsistent with a drifting period. Observed rotating asymmetries of the magnetosphere are unlikely to have sufficient inertia to maintain a slowly varying periodicity. The ionosphere/thermosphere/upper atmosphere with low enough inertia to allow drift and high enough inertia to maintain phase coherence is a plausible source region that is just now being investigated. We used a magnetohydrodynamic simulation [10] to characterize the response of the coupled magnetosphere-ionosphere to an atmospheric cyclone, a flow vortex fixed in the rotating southern thermosphere/ionosphere. The interaction is found to produce the following diverse magnetospheric responses observed during southern summer: (i) a rotating current system localized near 70° invariant latitude and flowing between the southern and northern ionospheres (the "cam current" [11]) that varies roughly sinusoidally with longitude and intensifies as it rotates into the morning sector, plausibly the source of SKR modulation; (ii) rotating magnetic perturbations roughly uniform inside of ~10 R_S; (iii) a rotating asymmetric ring current linked to periodically varying field magnitude; (iv) periodic motions of the tail current sheet beyond ~15 R_S; (v) periodic plasmoid releases in the tail; and (vi) periodic plasma injections into the middle magnetosphere. The model's success suggests that more detailed investigations of Saturn's upper atmospheric winds are imperative.

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