Fast rotating magnetospheres of giant planets

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The space environments of Jupiter and Saturn are complex, multiphase environments, consisting of solid surfaces of rings and moons, atmospheric neutral gas, charged particles and plasma populations trapped by the planetary magnetic fields, that are connected dynamically and chemically.

These small planetary systems in their own rights have attracted considerable attention over the last few decades with several major robotic space-based missions sent, or planned, to explore them and their local environment : the system of Saturn has been studied in detail since June 2004 (and will be until 2017) by the NASA/ESA Cassini-Huygens mission, the NASA Galileo mission has orbited Jupiter during 8 years from 1995 until 2003, the NASA Juno mission will insert into a polar orbit around Jupiter in 2016, while the ESA JUICE (JUpiter ICy Moon Explorer) mission is currently under study for a launch in 2022.

In the magnetic cavities (magnetospheres) of giant planets such as Jupiter and Saturn, plasma sources are abundant. These may be created by the solar wind, in the atmosphere of the planets, in their ionosphere, or by their moons (in particular Io at Jupiter and Enceladus at Saturn). The situation is significantly more complex than even the terrestrial case where external (solar wind) and internal sources (ionosphere/atmosphere) are comparable. As a result, the magnetospheres of the giant planets contain uniquely diverse regions compared with those observed elsewhere in the solar system. Understanding these regions, their equilibrium and dynamics, and their coupling via the transfer of mass, momentum, and energy at their interfaces constitutes both observational and theoretical challenges.

Plasma motions in magnetospheres are usually driven either by the environment or by the rotation of the central body. At Earth, the solar wind constitutes the primary source of motions in most of the magnetosphere, whereas the bulk of the Jovian and Saturnian magnetospheres are largely dominated by the rapid planetary rotation.

The purpose of the present paper is to review the main properties of rotation-dominated magnetospheres based on a fundamental process approach. This will be the strong unifying theme of this paper. I will focus here on several categories of processes occuring in the fast rotating magnetospheres of giant planets, starting with the basic processes shaping these planetary space environments, enlighting then the processes responsible for the magnetospheric dynamics, and concluding with the more original processes arising from the multiphase interactions operating in these complex environments. Illustrations of these processes will be taken when possible from observations obtained by orbiting spacecraft or earth-based observatories. The case of Saturn will be favored since its magnetosphere is currently studied from the microphysical to the global scale by the Cassini-Huygens mission.

Basic processes shaping giant planet magnetospheres

The contribution of the internal plasma sources is, by far, dominant in giant planet magnetospheres. The thermal plasma freshly created by the internal sources is trapped by the planetary magnetic field and entrained by the fast planetary rotation around the planet. The centrifugal force resulting from the rapid overall rotation (e.g., 1 Saturnian day lasts for approximately 10 hours and 39 minutes) confines the plasma towards the equatorial plane, giving rise to a thin disc of corotating plasma in the inner magnetospheric regions and stretching the magnetic field lines outwards. In steady state, since the plasma added locally cannot build up indefinitely, a circulation system is set up such that the plasma is either transported outward to the remote magnetospheric regions where it escapes into the interplanetary medium, or lost down the planetary field lines into the ionosphere.

The magnetically confined, centrifugally outward driven plasma and the corresponding highly stretched closed magnetic field lines form a magnetodisk in giant planet magnetospheres. Planetary magnetodisks are formed when significant ring current is present over an extended region, and the dipole planetary magnetic field becomes too weak to maintain stress balance and the current needs to intensify in order to balance the mechanical stresses [1].

I will provide a detailed discussion of these processes during my presentation. In particular I will introduce the basic theoretical aspects required to understand how the whole magnetospheres of Jupiter and Saturn are driven into corotation.

Fundamental plasma processes driving giant planet magnetospheres dynamics

First, magnetospheric dynamics includes the global flow of plasma mass and energy in both the corotational and non-corotational directions, as well as external (solar wind) or internal (planetary rotation) drivers.

Rapidly rotating planets with strong magnetic fields can enforce plasma flow in the corotation direction. Coupling between the magnetosphere and ionosphere drives the corotation of the magnetosphere, so the rotational velocity associated with corotation reflects the motion of the ionosphere, and not necessarily the motion of the planetary interior. Any drage forces in the magnetosphere can cause the magnetosphere motion to deviate from and lag behind the ionospheric motion.

I will address the rotational versus solar-wind drivers of plasma transport within giant planet magnetospheres and in their coupled magnetosphere-ionosphere-thermosphere systems. I will in particular discuss the role of the centrifugal interchange instability [2] as a source of plasma dynamical features and associated transport, sources and processes of rotational lag within giant planet magnetospheres. There are also a number of clear solar wind influences on the outer magnetospheres and magnetotails of Jupiter and Saturn that I will discuss.

Second, magnetospheres are large-energy-storage reservoirs. Of particular interest are the mechanisms leading up to both storage and emptying of these reservoirs, and those which convert energy from one kind of magnetospheric energy to another. These processes include 1) magnetic reconnection, 2) a variety of particle acceleration mechanisms and 3) wave-particle interactions that can be used to remotely diagnose magnetospheric dynamics.

All these processes have close analogues in other magnetospheres or space environments, albeit under very different conditions. I will compare and contrast our understanding of these processes at giant planets and at Earth [3].

Fundamental multiphase processes operating in giant planet magnetospheres

An important recycling of matter takes place in giant planet magnetospheres, through a number of multiphase interactions and dynamical processes [5]. Dust particles strongly interact with the planetary magnetic field and with the ambient plasma and are important sources and sinks for plasma species. The ionisation of neutral species is the dominant source of magnetospheric plasma and occurs deep inside Jupiter's and Saturn's magnetosphere, at the first extremity of this cycle. The neutral gas within the inner magnetosphere not only is the source of the magnetospheric plasma, but it also interacts with the plasma through the process of charge-exchange, in which an electron from a neutral atom or molecule is transferred to a passing ion, turning the neutral into an ion and the ion into a neutral, but changing the velocity of neither particle. The resulting neutral speeds off with the straight-line velocity that it had as an ion at the instant of charge transfer, which is typically much faster than the Keplerian velocity. Such fast neutrals, which are no longer gravitationally bound to Saturn and thus leave the system, provide the means for remote imaging of the magnetospheric population through ENA imaging. The creation of a new ion in the presence of Saturn's magnetic field and corotational electric field leads to the process of ion pick-up. A number of waves and dynamical processes observed in giant planet magnetospheres are also used as diagnostics of both the plasma and the neutrals being ionised, and the plasma to be transported outward to the remote magnetospheric region. Brightenings in ENA emissions, magnetic reconnection and plasmoid release, ultimately enable the plasma to leave the magnetosphere, at the second extremity of the cycle.

Jovian and Saturnian moons act as aborbers of charged particles and mass load the magnetospheres, either by the sputtering of surfaces or atmospheres, or by its geologic activity (Io at Jupiter, Enceladus at Saturn). Surfaces in space that are weathered by impacting photons, charged and neutral particles and dust grains can give clues to an orbiting spacecraft as to the composition of the planetary habitats and weathering of the surface material.

I will review 1) some of the mechanisms that provide material sources of gases and plasmas within Jupiter's and Saturn's space environments, 2) charged particle and plasma interactions with surfaces and neutral gases, and 3) moon-magnetospheres interactions.

Figure 1 displays Cassini multi-instrument observations obtained during Saturn Orbit Insertion. This illustrates the richness of these datasets at Saturn, with a particular emphasis on magnetospheric regions and physical processes operating in this complex environment. At the end of the Cassini mission in 2017, Saturn's magnetosphere will be the most detailed magnetosphere after the one of the Earth, while our understanding of the one of Jupiter will significantly improve in the near future with new missions en route to the planet. Comparative studies of these three magnetized environments combining data analysis, theroretical modelling, numerical simulations as well as laboratory experiments will undoubtedly bring new insights into our understanding of the plasma Solar System.

References

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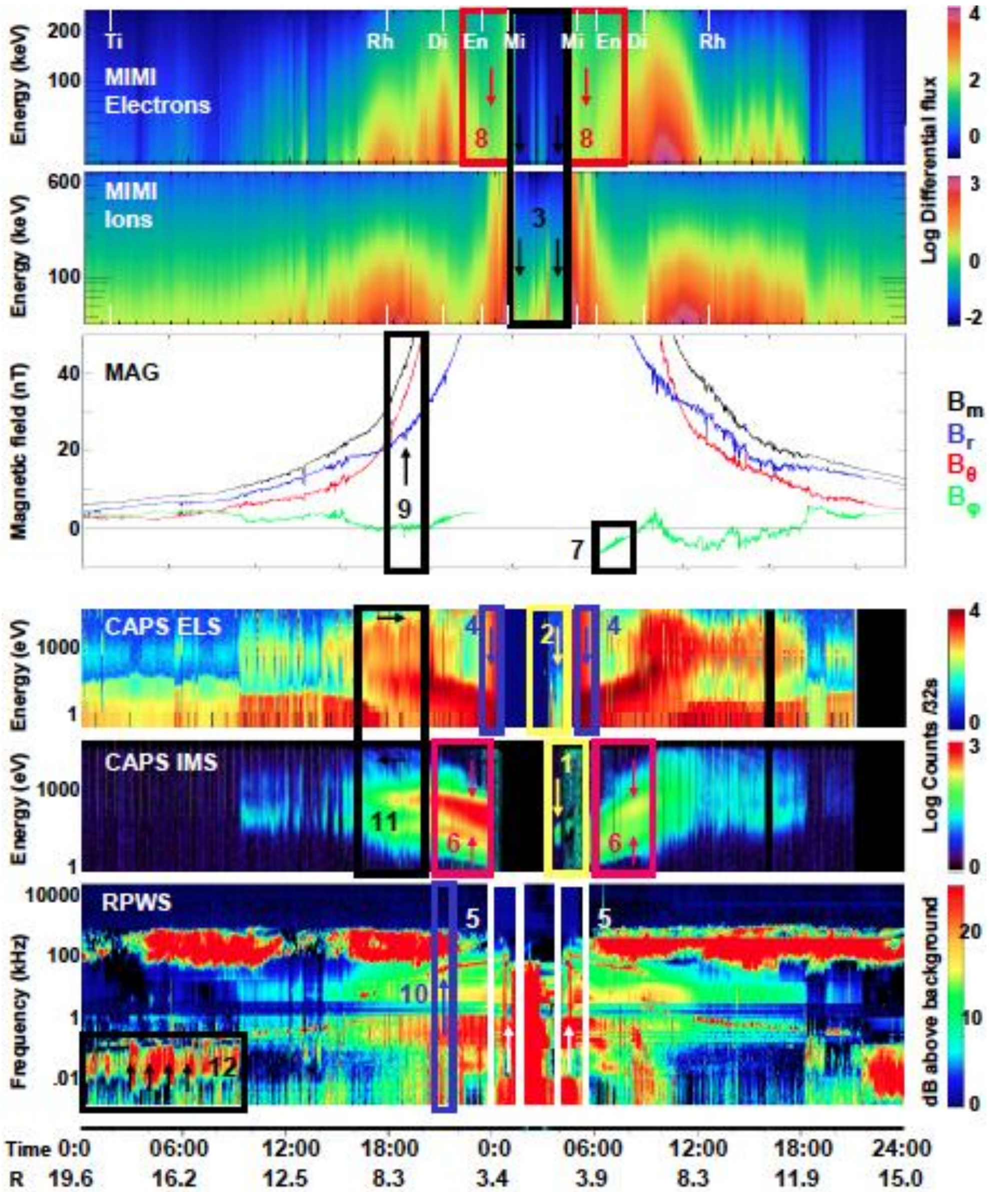

Figure 1: *Multi-instrumental view of the Saturnian magnetosphere, from June 30 00:00 UT (DOY 182) to July 2 (DOY 184) 00:00 UT. From top to bottom: Color-coded MIMI LEMMS energy (in logarithmic scale)-time spectrograms of 1) electron and 2) ion intensities (in logarithmic scale, cm−2sr−1s−1keV−1); 3) MAG magnetic field components in a Saturn-centered polar spherical coordinate system (the radial one in blue, −Br; the theta one in red, Bθ; and the azimuthal one in green Bφ) and magnitude (in black, Bm); Color-coded 4) CAPS ELS and 5) IMS energy (in logarithmic scale)-time spectrograms of electron and ion counts (in logarithmic scale); and 6) Color-coded (in logarithmic scale) RPWS electric field frequency (in logarithmic scale)-time spectrogram, versus time (in hours) and radial distance (in Rs). Vertical lines are used in section 5 to describe a unified picture of the four different magnetospheric regions and delineate their boundaries. CA indicates Closest Approach. The locations of some of Saturn's moons are indicated in the first panel and repeated in the second one. Notations for moons: Ti, Titan; Rh: Rhea; Di: Dione; En: Enceladus; Mi: Mimas. This serves here to enlight the following fundamental plasma and multiphase processes : 1) Ring ionosphere; 2) Electron plasma above the rings; 3) Energetic particles absorption by ring particles; 4) Radiation belts; 5) Dust impacts; 6) Water magnetosphere; 7) Ion cyclotron waves from engine exhaust; 8) Depletion of hot electrons and charge exchange processes; 9) Unusual magnetic flux tubes; 10) Density cavities; 11) Energy-time dispersed injection of hot plasma; 12) Modulations of whistler-mode waves.* [6]