Saturn: Atmosphere, Ionosphere, and Magnetosphere

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The Cassini spacecraft has been in orbit around Saturn since 30 June 2004, yielding a wealth of data about the Saturn system. This review focuses on the atmosphere and magnetosphere and briefly outlines the state of our knowledge after the Cassini prime mission. The mission has addressed a host of fundamental questions: What processes control the physics, chemistry, and dynamics of the atmosphere? Where does the magnetospheric plasma come from? What are the physical processes coupling the ionosphere and magnetosphere? And, what are the rotation rates of Saturn's atmosphere and magnetosphere?

Saturn is the only planet for which we don't know the wind speed. We can see the planet rotate by tracking clouds in its atmosphere, but the clouds move relative to each other, and their average speed is not necessarily that of the planetary interior. The intrinsic magnetic field is no help because it is symmetric about Saturn's spin axis. The relative speeds are large, up to an order of magnitude larger than on Earth, which is a mystery because the incident sunlight at Saturn is only 1% that at Earth.

There are multiple condensates and multiple cloud layers in Saturn's atmosphere. Hydrocarbon chemistry dominates because methane is an abundant gaseous constituent. Disequilibrium species arise because of absorption of energetic photons, rapid vertical transport, electrostatic discharges, and bombardment by charged particles from Saturn's magnetosphere. Sorting these processes out is a major challenge that teaches us about atmospheric chemistry and evolution.

Most of the plasma in Saturn's magnetosphere originates from the rings, Enceladus, and other icy satellites. In this respect, the Saturn system is similar to Jupiter and different from Earth, where the solar wind is the primary plasma source. This difference arises because the solar wind is two orders of magnitude less dense at Saturn and the interplanetary magnetic field is an order of magnitude weaker than it is at Earth. Also, the rotation rates for Jupiter and Saturn are ~2.5 times faster than Earth's, and their radii are ~10 times larger, so centrifugal forces play a much larger role.

Atmosphere

Winds and planetary rotation. On a fluid planet, the wind is measured relative to the interior. Cloud features, which are roughly at the 1-bar level, move from west to east, circling the planet at periods ranging from 10 hours and 10 min to 10 hours and 40 min. Each latitude band has its own circulation period, indicating that different latitude bands have different wind speeds. The question is whether observations of the atmosphere can be used to infer the rotation rate of the interior. Cloud-tracked wind data from Voyager showed that the average period is between 10 hours and 31 min and 10 hours and 32 min. A least-squares fit to the oblate shape of the 100 mbar surface gives an estimate of 10 hours and 32 min 35 ± 13 s for the interior period (*1*). The potential vorticity (PV) gradient, which is related to the curvature of the wind profile with respect to latitude, implies an internal period of 10 hours and 34 min 13 ± 20 s (*2*). These methods work reasonably well for Jupiter, for which we know the internal period, but there is no guarantee that they work for other planets. For instance, Venus has an atmospheric period at the 100-mbar level of 4 days, even though the planet's internal rotation period is 243 days.

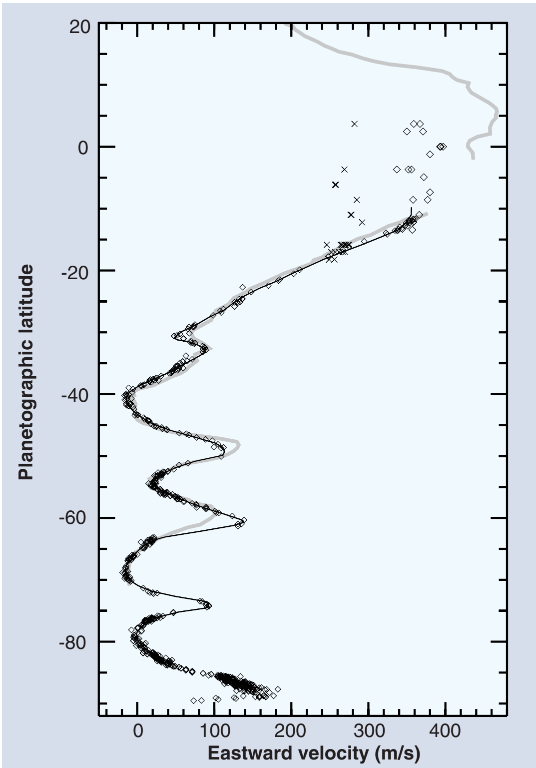

Fig. 1. Eastward velocity obtained by tracking clouds in sequences of images. The winds are shown relative to a uniformly rotating coordinate system that was defined after the Voyager encounters from the SKR radio emissions. A. Vasavada created this figure from published Voyager and Cassini data (*9*, *35*, *36*). The velocities are obtained by tracking clouds in sequences of images. The crosses and diamonds are from images at 727 nm (which senses relatively high altitudes) and 750 nm (which senses lower altitudes), respectively. The thin dark line is a fit to the 750 nm data, and the thick gray line is a fit to Voyager data in a broadband filter that senses lower altitudes. The rings obscured the northern hemisphere when the Cassini data were taken, and they obscured the band from 2° to 11°S when the Voyager data were taken.

Cassini and Voyager data show that outside the equatorial region, the winds are remarkably steady by Earth standards (Fig. 1). The winds at the equator vary by ~200 m s^{-1}, which is 10 times larger than the variation of Earth's jet streams. Whether this is a variation with time or a variation with altitude is still an open question (*3*). Nevertheless, some slowing seems to have occurred over the 25 years between Voyager and Cassini. Winds in the stratosphere, above the 10-mbar level, seem to vary by ±75 m s^{-1} with altitude and time in a manner reminiscent of Earth's quasibiennial oscillation (QBO) (*4*, *5*). Saturn's large differential rotation, which is larger than that of Jupiter, is still unexplained.

A key question is, what maintains the jets against friction? Eddies carry momentum north and south between neighboring eastward and westward jets, and they can either add momentum to the jets or subtract it. If the eddies are tilted northeast-southwest (NE-SW), then they are transporting eastward momentum to the north. If they are tilted NW-SE, then they are transporting westward momentum to the north. In the NW-SE case, if there is a westward jet to the north and an eastward jet to the south, then the jets are gaining energy from the eddies. Such eddy-to-mean-flow energy transfer has been observed on Earth, Jupiter (*6*), and Saturn (*7*). Where the eddies get their energy is still an open question.

Polar vortex and hexagon. The eastward jet at 88° to 89°S is a cyclonic vortex with low clouds and high atmospheric temperatures at its center (*8*). The clouds at 88° to 89°S tower 50 to 70 km above the clouds at the pole (*9*). The combination of clockwise flow, high central temperatures, and a ring of high clouds surrounding a central "eye" are features of hurricanes (tropical cyclones) in Earth's southern hemisphere. However, the Saturn eyewall clouds are ~4 times higher than those on Earth (*9*). Also, the eye on Saturn has a diameter of 2000 km, which is 20 to 40 times that of a terrestrial hurricane. Other differences are that the structure is fixed at the south pole and operates

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without an ocean below it. Saturn has no long-lived anticyclonic ovals that rival Jupiter's Great Red Spot.

Saturn's northern hemisphere also has a warm eye at 88° to 89°N with a hurricane-like vortex (Fig. 2). The next jet to the south, at 75°N, is part of the north polar hexagon. This pattern in the clouds has been in existence since Voyager detected it in 1980. Small clouds move counterclockwise around the hexagon, following its outer boundary at a speed of ~100 m s^{-1}. The hexagonal pattern is probably a wave that just happens to fit six times around the globe at this latitude. The difficult questions are, why is the wave stable and what is special about this jet that causes it to develop waves?

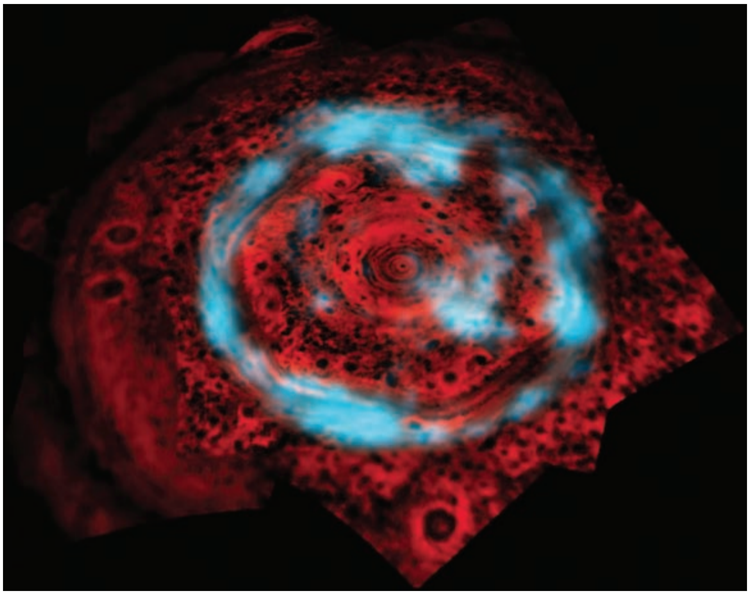

Fig. 2. North polar hexagon (red) and aurora (blue) in the thermal infrared (PIA11396). Red shows 5 μm emission coming up through holes in the clouds. Blue shows 3.67 μm emission from H_3^+ ions in Saturn's auroral zone.

Storms. Every few years, Saturn has a lightning storm. We have not seen the flashes because light from the rings makes the night side of the planet too bright. But we "hear" the lightning on Cassini's short-wave radio, the Radio and Plasma Wave Science (RPWS) instrument (*10*). The storms last for weeks or months, and usually there is only one. A storm in 2004 produced three active centers, α, β, and γ, over a 24-day period (Fig. 3). Each center spent a few days in the active phase, producing high dense clouds, and then it became a stable dark spot that drifted off to the west and lasted for weeks or more. The radio emissions were hundreds of times brighter than those from a terrestrial storm. All of the storms observed since 2004 have been in the same westward jet at 35°S planetocentric latitude (~40° planetographic). Great equatorial storms, which sometimes encircle the planet, erupt at 15- to 20-year intervals. The last such storm occurred in 1990.

Upper atmosphere. Diffusive separation, in which each gas follows its own scale height, occurs above a certain altitude called the homopause. Atmospheric turbulence, on the other hand, tends to maintain the gases in a well-mixed state. The turbulence is usually maintained by breaking waves that propagate up from below, but the sources and mechanisms are often mysterious. Wave-breaking can also heat the upper atmosphere. The heated region is called the thermosphere, which merges into the exosphere, where the molecules follow ballistic trajectories before falling back into the gaseous atmosphere.

Above the homopause, the heavier gases like C_2H_2 and CH_4 separate out, and He, H_2, and H eventually dominate. On Saturn, the homopause height is highly variable, suggesting large variability in the propagation of waves from below. The cause of this variability is not known, nor is the dominant source of heat for the thermosphere. Interaction with the magnetosphere through ion drag is a candidate. Other candidates are photolysis and wave-breaking. Thermospheric temperatures are in the range of 300 to 450 K (*11*). Cooling is by conduction to deeper layers that radiate the energy to space.

Ionosphere and Aurora

Ionosphere. Electron density profiles from Cassini (Fig. 4) (*12*) show that both the average electron density and the peak altitude increase with latitude. A decrease in the mean peak density and increase of its height from dusk to dawn was also seen in the average low-latitude observations, which is consistent with the presence of molecular ions, which decay rapidly at sunset. The large variability of electron densities observed at similar latitudes and times suggests that dynamical and/or electrodynamical processes control Saturn's ionospheric structure. The main daytime ionization source is photoionization. The ion lifetime is reduced by water, which comes from the rings and icy moons.

Only H_3^+ ions have been directly observed, by means of infrared remote sensing (*13*). H_3^+ has three strong emission lines near 3.67 μm, and they constitute the infrared aurora shown in Fig. 2. H^+ and H_3^+ are the dominant ions in Saturn's ionosphere. H_2^+ is scarce because it is rapidly converted to H_3^+. The fast dissociative recombination of H_3^+ means that it has a strong diurnal variation, with a minimum just before sunrise.

The ionospheric temperature profile has also been estimated by using radio occultation data and theoretical models. These calculations obtained plasma temperatures in the 1500 to 3000 K range, with peak ionospheric densities of ~10^4 cm^{-3} (*12*). The plasma outflow rate from the high-latitude ionosphere to the magnetosphere was estimated to be ~1 kg s^{-1}, which is somewhat lower than the source rate of magnetospheric plasma from the rings but larger than the Titan-associated plasma source (*14*).

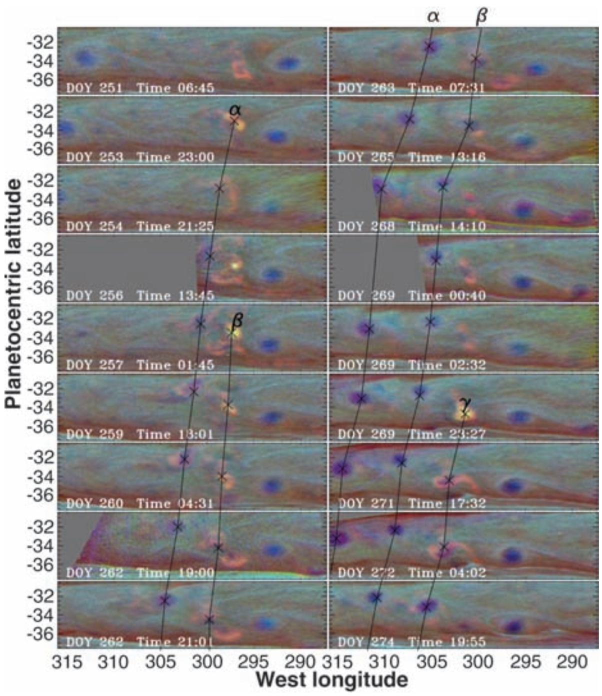

Fig. 3. False-color image showing depth variations of the 2004 lightning storm with time (*37*). The red, green, and blue color planes of the image show the clouds at 750, 727, and 889 nm, and are sensitive to deep, intermediate, and high clouds, respectively. The white spots are light, thick clouds suggestive of moist convection (*35*). The blue spots are likely high, thin clouds, but they could also be clouds with a dark coating on the particles. Carbon released from methane by lightning is one such coating material (*38*). The figure shows the birth of these active centers, α, β, and γ, which start out as high thick clouds and gradually turn dark. The dark spots drift off to the west and can last for weeks or more (*35*).

Aurora. As on Earth, the aurora is caused by energetic particle precipitation. The ultraviolet (UV) radiation is from excited atoms and molecules that are not in thermal equilibrium. The infrared radiation is from the heated atmosphere and is essentially thermal radiation (Fig. 2). The bright ring had been seen from Earth, but the bright auroral emission within the polar cap had not been detected until Cassini. The auroral emission arises hundreds of kilometers above the clouds that are seen at 5 μm. The main auroral oval is often incomplete, forming a spiral that does not close upon itself. Often there are auroral bright arcs near dawn that rotate at a fraction of the rotation rate of the magnetosphere, with the bright spots moving poleward in the afternoon as they fade. Disturbed conditions, triggered by solar wind compression regions, result in the poleward expansion of the main oval, particularly on the dawn side (*15*). The balance between solar wind control and the effect of planetary rotation is still under investigation.

Magnetosphere

Intrinsic magnetic field and periodicities. Saturn's internal magnetic field is generated in the electrically conducting region that begins approximately one third of the way down to the center of the planet. For most planets, including Earth and Jupiter, the magnetic and rotation axes are sufficiently different so that periodicities in the magnetosphere provide information about planetary rotation. Because Saturn's internal magnetic field is nearly axially symmetric around the rotation axis, the internal rotation rate cannot be inferred from magnetospheric periodicities.

One such periodicity is the SKR, or Saturn kilometric radiation. The two Voyager spacecraft measured the SKR period in 1980 and 1981 and found it to be 10 hours, 39 min, and 24 s. This was slower than most of the visible atmosphere but within the range of atmospheric periods and was taken to be that of Saturn's interior. However, the Cassini spacecraft has shown that the SKR period is variable (*16*) (Fig. 5). Because Saturn's period cannot vary appreciably over these short time scales, it appears that the SKR is not a reliable measure of the internal rotation rate.

Periodicities at or near a common rotation period of ~10 hours and 40 min are ubiquitous in the magnetosphere of Saturn. Because the rotation and magnetic axis are very closely aligned, the origin of these periodic modulations is still not understood, even though a variety of processes were suggested for its causes (*17*, *18*). Periodicities have long been recognized in the charged particles of Saturn's magnetosphere. In particular, charged particles with energies above 20 keV display periodicities very close to the SKR period. Energetic neutral H and O atoms also show modulations near the SKR frequency (*19*). Far out in the magnetotail, there are magnetic field periodicities that are close to the rotation period of Saturn (*20*).

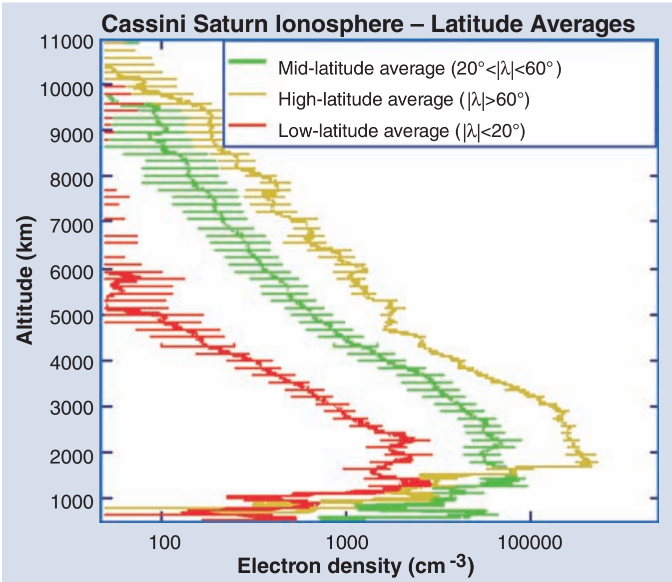

Fig. 4. Averaged near-equatorial dusk and dawn electron-density profiles observed by Cassini (*12*).

Plasma sources. Observations from the first close Cassini flyby revealed the surprising fact that Enceladus is actively venting gas and ice grains (*21*–*24*). These observations also showed that H_3O^+ ions were dominant around Enceladus. The primary gas emitted is water vapor, potentially accounting for the observed vast cloud of water vapor and water products. UV stellar occultations and a detailed analysis of the in situ particle observations yielded a total plasma production rate of ~300 kg s^{-1} (*22*, *25*).

Enceladus is also the source of ions for the ring current, which circles the planet in the equatorial plane and is generated by the longitudinal drift of energetic charged particles trapped on closed magnetic field lines. The ring current plays a major role in determining the magnetic field configuration. It is primarily composed of accelerated water group ions (*26*, *27*), which strongly points to Enceladus as the main plasma source.

Deep inside the inner plasma source region, Cassini measurements revealed the existence of a tenuous plasma layer in the vicinity of Saturn's main rings (*26*, *28*, *29*). The ion composition of this "ring ionosphere" consists of O^+ and O_2^+. These ions are likely produced by UV photosputtering (particle emission caused by photon absorption) of the icy rings, with subsequent photoionization of the O_2 (*26*, *29*).

The radial dependence of the N^+ density and the energy of this population point to a source in the inner magnetosphere: most likely Enceladus (*30*). This is surprising because before Cassini, Titan was expected to be a major source of magnetospheric N^+ ions. This lack of nitrogen is probably attributable to the inability of flux tubes at Titan's large orbital distance to execute complete drift orbits around Saturn, so that Titan-originating plasma cannot build up to substantial densities. Whatever the reason, there is no evidence in the inner magnetosphere for appreciable amounts of plasma of Titan origin.

Convection and plasma drainage. There are two types of magnetospheres, those like Jupiter and those like Earth. Saturn is in between. The terrestrial magnetosphere is solar wind–controlled, and the magnetospheric circulation is referred to as the "Dungey cycle" (*31*). The process starts at the dayside magnetopause, in which planetary magnetic field lines and the southward component of the interplanetary magnetic field (IMF) reconnect, creating open magnetic field lines originating from the high-latitude ionosphere and extending to the free-flowing solar wind. These open field lines form the open flux magnetospheric tail lobes (North and South). The open flux tubes close by reconnecting behind Earth on the night side, and the process repeats.

Jupiter is a fast rotator with a strong surface magnetic field, so internal processes dominate the magnetosphere out to ~100 times Jupiter's radius, and the Dungey cycle is only marginally important. Io produces plasma deep inside Jupiter's magnetosphere at a rate of ~10^3 kg s^{-1}, and this adds considerable "new mass" to the corotating magnetic flux tubes. The magnetic field lines remain attached to the corotating ionosphere and are stretched outward by the heavy equatorial plasma. The current system intensifies in order to balance the mechanical stresses. The centrifugal force acting on the newly produced plasma at Io exceeds the gravitational force by a large factor and only magnetic forces can confine the plasma. This magnetically confined, centrifugally outward–driven plasma and the corresponding highly stretched closed magnetic field lines form what is called the magnetodisk.

If the equatorial quasi-dipolar field cannot maintain stress balance with the plasma stresses, the field will become more and more stretched. Quasiperiodically, the field lines become so stretched and thin that they "break," and a magnetic loop with high plasma content (a plasmoid) is formed that can now freely move down the magnetotail. The shortened empty field lines return to the inner magnetosphere via the interchange process (*32*). This circulation process is called the "Vasyliũnas cycle" (*33*).

Cassini showed that Saturn's magnetodisk is bowl-shaped and bent upward from the equator (toward ecliptic north) (*34*). During the season, Saturn's magnetic south pole was tilted toward the Sun (Saturn's magnetic dipole is oppositely

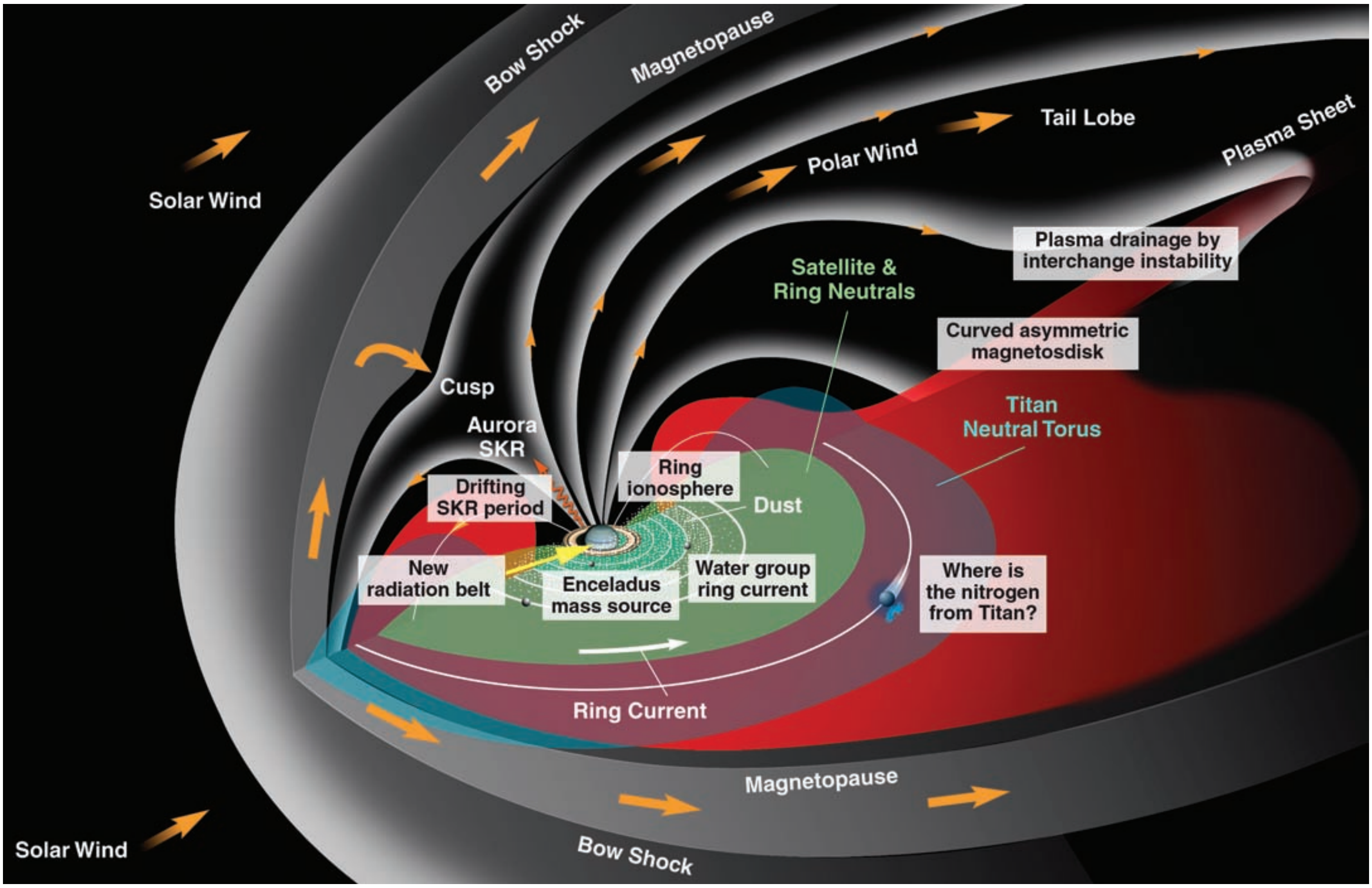

Fig. 5. Main magnetospheric results of the Cassini mission that are discussed in the text [background figure is courtesy of the Cassini Magnetospheric Imaging Instrument (MIMI) team].

oriented that of Earth). This is different from Jupiter, where the magnetodisk warps downward, and from Earth, where the magnetodisk is absent (there is no magnetospheric plasma source). Causes for this warping are still being debated.

Saturn falls somewhere between Earth and Jupiter, and is therefore more complex. It is a fast rotator, but the equatorial magnetic field is comparable with that of Earth. The magnetospheric mass source (Enceladus) is a factor of three smaller than that of Jupiter (Io). As a result of this intermediate parameter range, Saturn's magnetosphere exhibits both a Dungey cycle and a Vasyliũnas cycle at the same time (*19*).

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