GAS GIANT PLANETS

In situ measurements of Saturn's ionosphere show that it is dynamic and interacts with the rings

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The ionized upper layer of Saturn's atmosphere, its ionosphere, provides a closure of currents mediated by the magnetic field to other electrically charged regions (for example, rings) and hosts ion-molecule chemistry. In 2017, the Cassini spacecraft passed inside the planet's rings, allowing in situ measurements of the ionosphere. The Radio and Plasma Wave Science instrument detected a cold, dense, and dynamic ionosphere at Saturn that interacts with the rings. Plasma densities reached up to 1000 cubic centimeters, and electron temperatures were below 1160 kelvin near closest approach. The density varied between orbits by up to two orders of magnitude. Saturn's A- and B-rings cast a shadow on the planet that reduced ionization in the upper atmosphere, causing a north-south asymmetry.

The gas giant planet Saturn is composed primarily of hydrogen and helium. The upper, tenuous parts of its atmosphere are partially ionized (producing ions and electrons), foremost by the solar extreme ultraviolet (EUV) radiation, but also by energetic particle impacts originating from the planet's magnetosphere and cosmic rays. The result is an electrically charged layer, the ionosphere, situated approximately between 300 and 5000 km altitude (*1*). By convention, the reference altitude of 0 km is at a pressure of 1 bar and is set to a distance of 60,268 km from the center of Saturn. So far, three methods of remote sensing have been used to infer the properties of Saturn's ionosphere: radio occultation (*2*–*5*), radio emission from Saturn's electrostatic discharges (*6*, *7*), and millimeter-band observations of protonated molecular hydrogen (H_3^+) (*8*). These measurement methods do not reveal small-scale variations (at scales below 1000 km); they only provide average constraints on the processes occurring in Saturn's ionosphere. In addition, the first two of these methods only derive the electron density, which, in the presence of abundant organic or water cluster ions (positively and negatively charged), does not give a representative picture of the true ionospheric densities (*9*, *10*). Nevertheless, the radio occultation data set reveals a decrease in the plasma number densities toward lower latitudes and somewhat higher densities toward local dusk (*2*–*5*).

We present in situ measurements of Saturn's topside ionosphere from the Cassini spacecraft. The spacecraft first encountered the ionosphere around 09:00 UT on 26 April 2017 (Fig. 1) and continued to do so every ~6.5 days during the subsequent orbits. Data from the first 11 orbits are considered in this paper. The closest approach during the first encounter occurred at an altitude of 2800 km and varied from 2600 to 4000 km during the subsequent 10 crossings. Two types of data were collected using the Radio and Plasma Wave Science (RPWS) instrument package: Langmuir probe measurements and observations of whistler-mode emissions, from which the electron plasma frequency (f_{pe}) was determined (*11*). Above 1500 km altitude, the hydrogen ions (H^+ and H_3^+) are expected to be the dominant ionospheric species, whereas methane and other heavier species become important for the ionospheric chemistry below this altitude (*12*). All the crossings that we present occurred between 11 and 14 hours Saturn local time (LT) (table S1).

Figure 2 shows the altitude profiles of the electron and ion number densities (Fig. 2A) and the electron temperature (Fig. 2B) derived from the RPWS measurements during the first Cassini ring and ionosphere crossing on 26 April 2017. By comparison with Fig. 1, it can be seen that the altitude profiles in Fig. 2 really are convolutions of latitude and altitude. During this initial flyby of the ionosphere, the scale height varied between 1000 and 1500 km. The combination of a dense plasma (reaching 1000 cm^{-3} near closest approach) with a decreasing electron temperature (to below 0.1 eV or 1160 K) on approaching the planet indicates the detection of the cold and dense ionosphere of Saturn. Theoretical ionosphere modeling results indicate that electron temperatures near noon at 3000 km altitude could reach 500 K (*12*). However, the measured electron temperature data presented here are variable at altitudes up to 7000 km, contrary to the theoretical predictions.

From the inbound ion density measurements in Fig. 2A, we conclude that Saturn's ionosphere was dominated by H^+ ions during this flyby. This conclusion holds in most of the data from all 11 flybys. One exception is the flyby on 4 June 2017 (orbit 277; Fig. 3), where RPWS detected the signature of a heavier dominant ion species [>18 atomic mass units (amu)] near the equator, which is also related to differences in ion and electron densities indicative of the presence of negatively charged nanometer-sized grains or cluster ions. Orbit 277 is also one of the crossings closest to the D-ring (*13*) and the

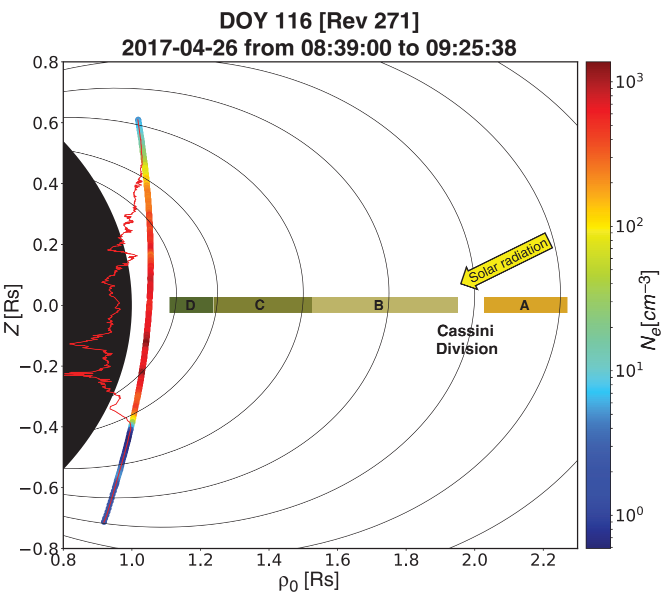

Fig. 1. Electron density (N_e, colored band) measured by the Cassini Langmuir probe on 26 April 2017. The spacecraft crossed through the gap between the planet Saturn (solid black) and its rings (denoted D, C, B, Cassini division, and A), passing from north to south. The color code signifies the measured electron number density (N_e), which is also shown as a red line (shown in linear scale; the density increases toward the left, with a maximum density of 1300 cm^{-3}). Four dominant electron density enhancements are mapped along Saturn's magnetic field to, or inside, the inner edge of the D-ring at the equator. The solar elevation angle was 26.7° during the event, and the shadows of the A-ring and part of the B-ring result in decreased ionization in the south. DOY, day of year; rev, orbit; R_S, Saturn radius; ρ_0, distance from Saturn.

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most distant of the crossings, with closest approach near 4000 km altitude. We interpret this observation as a detection of ionized material from the nearby D-ring.

The rings cast shadows on Saturn. On the basis of data from the first 11 flybys, the A- and most of the B-ring must be opaque to solar EUV because very little plasma was detected in the regions within the geometric shadows cast by these rings (Fig. 2A and figs. S2 and S3). The dropout of ionization corresponding to the shadow from the middle of the B-ring near 1.7 Saturn radii (R_S) (Fig. 1) is at a location where there are SOI (Saturn orbit injection) observations of a B-ring source of whistler-mode emissions indicative of field-aligned currents (*14*) and a related plasma cavity (*15*). A plasma sink near the rings would lead to enhanced diffusion at magnetically connected higher latitudes (>35°), suppressing the plasma density at that point in the ionosphere. The Cassini division is somewhat less opaque to EUV, whereas no effects can be detected for the D- and C-rings (which thus must be EUV-transparent). The enhanced ionization of the ionosphere where it is illuminated by light passing through the Cassini division, compared with the area in the shadow of the opaque A- and B-rings (Fig. 2A), is detectable in all 11 flybys (figs. S2 and S3). The low levels of ionospheric plasma observed by RPWS in the shadowed regions (for latitudes between –20° and –40°) indicate that no major transport of plasma occurs from nearby regions. The lack of emitted photoelectrons detected by the Langmuir probe in this region confirms the low level of photoionization (figs. S2 and S3). Theoretical predictions of reduced ionization owing to the ring shadows may explain why radio emissions from Saturn's electrostatic discharges leak out from lower atmospheric layers past the ionosphere peak (*16*).

The observations put constraints on the possible transport of charged water products from the rings along conjugate magnetic field lines (also called ring rain), as indicated by remote infrared H_3^+ emissions (*8*, *17*). A steady influx of water ions would react quickly with atmospheric hydrogen, recombining to neutral species, thereby removing the ionized component much faster than if only H^+ recombined with electrons (*18*). An inflow of large quantities of heavy ions from the C-ring along connected magnetic flux tubes is not confirmed by the RPWS observations in the shadowed ionosphere region (Fig. 4). The question of ring rain at higher latitudes (>35°) is not yet constrained by the data.

Figure 4 shows the large variability and fine structure of Saturn's ionosphere. Maximum electron densities span a wide range, 50 to 1300 cm^{-3}, which cannot be explained by a simple scale height model of a quiet ionosphere in photochemical equilibrium. One possibility is that a ring rain–like mechanism operates here, where variable amounts of water group (or molecular) ions originating from the D-ring material (near the equator or along connecting magnetic flux tubes) cause sporadic electron depletions. Electron depletions are evident within ±10° latitude during orbits 272, 273, 275, 277, 278, 280, and 281 (Fig. 4). These suppressed electron density dips vary between 50 and 200 cm^{-3}. The equator crossings for orbits 276 and 277 occurred furthest away from the planet, around 4000 km altitude, which we expect to be inside the D-ring. An equatorial depletion of 50 cm^{-3} was detected during orbit 277, where the Langmuir probe also detected the presence of negatively charged cluster ions or nanometer-sized grains (Fig. 3). Orbit 276 does not show a clear depletion signature. However, it is difficult to explain the full dynamic range of almost two orders of magnitude between each flyby with this chemical process alone. There is no continuous evolution of plasma density from the first orbit to the last, and large variations can occur between adjacent orbits (e.g., orbits 277 and 278; Fig. 4).

The time constants for transport compete effectively with photochemistry, and thus the plasmas sampled depend strongly on dynamics. We therefore suggest that an electrodynamic interaction occurs between the ionosphere and the electrically charged D-ring via the strong magnetic field of Saturn. This would drive ionospheric ion outflows

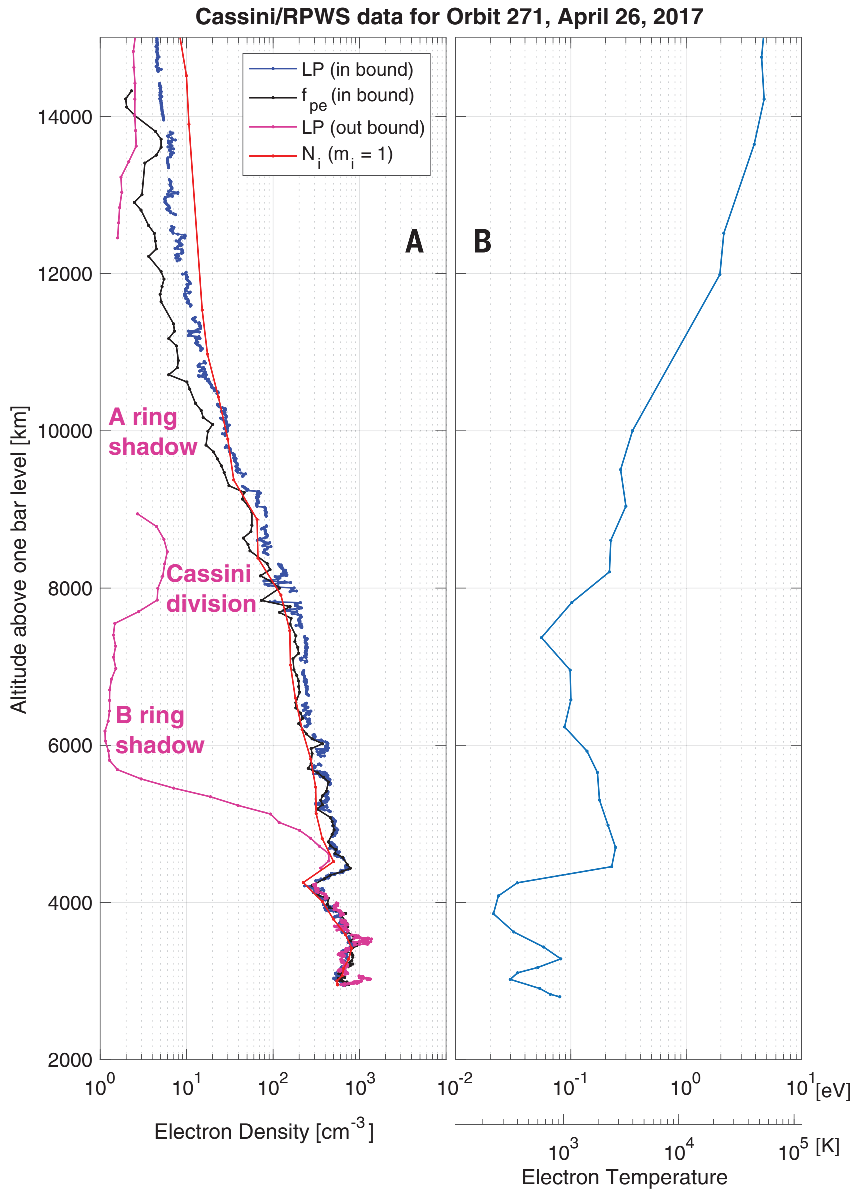

Fig. 2. Cassini RPWS altitude profiles of the ionosphere during the crossing on 26 April 2017. (**A**) Electron number density. (**B**) Inbound electron temperature. Two independent methods for estimating the inbound electron density (blue and black) gave almost identical results, confirming their validity. The Langmuir probe (LP) ion density [N_i, assuming the mass (m_i) of H^+] also produces values that agree with the estimated electron densities, confirming that hydrogen ions dominated during this flyby. The lower Langmuir probe electron densities over the outbound sector (magenta) indicate that much of the A- and part of the B-ring are opaque to ionizing extreme ultraviolet radiation. No whistler-mode cutoff data (black) exist for the outbound portion.

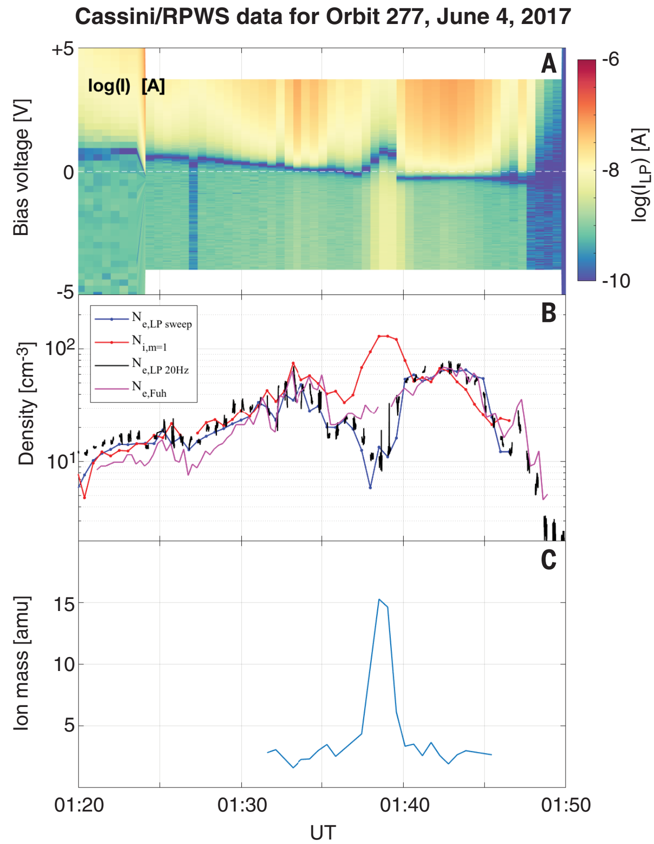

Fig. 3. RPWS data from an ionosphere crossing close to the D-ring of Saturn. (**A**) The Langmuir probe measured current (I) from voltage sweeps, (**B**) RPWS densities, and (**C**) inferred average ion mass. The electron densities (N_e) from three measurement methods (*11*) are lower than the estimated ion density (N_i) when Cassini passed the D-ring edge at 01:38 UT. The inferred average ion mass rose above 1 amu at this time. $N_{e,Fuh}$, electron density derived from the observed upper hybrid emission frequency.

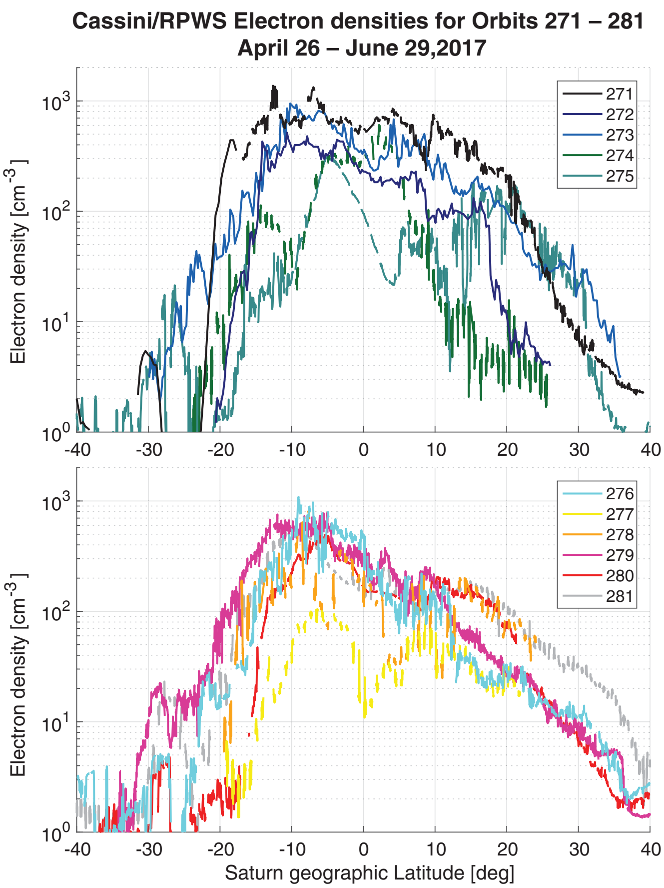

Fig. 4. RPWS electron number densities from 11 ionosphere crossings near the equatorial plane of Saturn. Densities for orbits 272 and 273 are based on whistler-mode cutoff data, whereas the rest are from the Langmuir probe measurements (the Langmuir probe was in the wake of the spacecraft during orbits 272 and 273). There are about 6.5 days between each flyby from 26 April to 29 June, all of which occurred close to 11 to 14 hours Saturn LT. The ionosphere exhibits large variability, with fine structure over these latitudinal-altitude cuts. The closest approach altitude occurs close to the geographic equator.

along magnetic flux tubes, leading to plasma structuring, as is observed along magnetic flux tubes above the aurora at Earth (*19*). The strong magnetic field of Saturn makes the rate of plasma-neutral collisions much smaller than the gyration frequency along the Cassini spacecraft trajectory; the ionospheric dynamo region, with coupling to neutral winds, is at a far lower altitude (*20*). The electrodynamics may instead be driven by the charged material in the D-ring (in Keplerian orbit) moving relative to the ionosphere (rotating with the planet), and a substantial cross–magnetic field current density may arise from the $\Delta\mathbf{V} \times \mathbf{B}$ term (where $\Delta\mathbf{V}$ is the relative speed of the two components and $\mathbf{B}$ is the magnetic field of Saturn). These ring currents then close via magnetic field–aligned currents to the conductive ionosphere below, with associated magnetic field–aligned ion flows along these flux tubes. Other possibilities for the variation in ionosphere dynamics involve strong longitudinal wind variations, coupled with variable EUV and X ionization levels, as is observed in Earth's ionosphere at ±20° latitude (*21*).

REFERENCES AND NOTES

1. J. Moses, S. F. Bass, *J. Geophys. Res.* **105**, 7013–7052 (2000).
2. A. J. Kliore *et al.*, *J. Geophys. Res.* **85**, 5857 (1980).
3. G. F. Lindal, D. N. Sweetnam, V. R. Eshleman, *Astron. J.* **90**, 1136 (1985).
4. A. F. Nagy *et al.*, *J. Geophys. Res.* **111**, A06310 (2006).
5. A. J. Kliore *et al.*, *J. Geophys. Res.* **114**, A04315 (2009).
6. M. L. Kaiser, M. D. Desch, J. E. P. Connerney, *J. Geophys. Res.* **89**, 2371 (1984).
7. G. Fischer, D. A. Gurnett, P. Zarka, L. Moore, U. A. Dyudina, *J. Geophys. Res.* **116**, A04315 (2011).
8. J. O'Donoghue *et al.*, *Nature* **496**, 193–195 (2013).
9. M. W. Morooka *et al.*, *J. Geophys. Res.* **116**, A12221 (2011).
10. O. Shebanits *et al.*, *Planet. Space Sci.* **84**, 153–162 (2013).
11. Materials and methods are available as supplementary materials.
12. L. Moore, M. Galand, I. Müller-Wodarg, R. Yelle, M. Mendillo, *J. Geophys. Res.* **113**, A10306 (2008).
13. M. M. Hedman, M. R. Showalter, *Icarus* **279**, 155–165 (2016).
14. L. Xin, D. A. Gurnett, O. Santolik, W. S. Kurth, G. B. Hospodarsky, *J. Geophys. Res.* **111**, (2006).
15. W. M. Farrell, W. S. Kurth, D. A. Gurnett, A. M. Persoon, R. J. MacDowall, *Icarus* **292**, 48–53 (2017).
16. M. Mendillo *et al.*, *Geophys. Res. Lett.* **32**, (2004).
17. T. G. Northrop, J. R. Hill, *J. Geophys. Res.* **87**, 6045 (1982).
18. L. Moore *et al.*, *Geophys. Res. Lett.* **33**, L22202 (2006).
19. J.-E. Wahlund, H. J. Opgenoorth, I. Häggström, K.-J. Winser, G. O. L. Jones, *J. Geophys. Res.* **97**, 3019–3037 (1992).
20. M. Galand, L. Moore, I. Mueller-Wodarg, M. Mendillo, S. Miller, *J. Geophys. Res.* **116**, 3019–3037 (2011).
21. H. Liu, C. Stolle, M. Förster, S. Watanabe, *J. Geophys. Res.* **112**, A11311 (2007).

ACKNOWLEDGMENTS

The Swedish National Space Board supports the RPWS/Langmuir probe instrument on board Cassini. W.M.F. gratefully acknowledges the Cassini project for internal NASA support. D.A.G., G.H., W.S.K., A.M.P., and S.-Y.Y. were supported by NASA through contract 1415150 with the Jet Propulsion Laboratory. All Cassini RPWS data are archived in the Planetary Data System Planetary Plasma Interaction node at https://pds-ppi.igpp.ucla.edu/search/?t=Saturn&i=RPWS on a prearranged schedule.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/359/6371/66/suppl/DC1
Materials and Methods
Figs. S1 to S4
Table S1
Reference (*22*)

18 July 2017; accepted 27 November 2017
Published online 11 December 2017
10.1126/science.aao4134

Science

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Science **359** (6371), 66-68.
DOI: 10.1126/science.aao4134originally published online December 11, 2017

Cassini enters Saturn's ionosphere
The upper reaches of most planetary atmospheres contain a layer that is ionized by incoming solar radiation––the ionosphere. As it went through its final orbits around Saturn, the Cassini spacecraft dipped close enough to the planet to pass directly through the ionosphere. Wahlund *et al.* examined the plasma data collected in situ and found that Saturn's ionosphere is highly variable and interacts with the planet's inner ring. They also observed decreases in ionization within regions shaded from the Sun by the rings.
Science, this issue p. 66