RESEARCH ARTICLE SUMMARY

GAS GIANT PLANETS

Chemical interactions between Saturn’s atmosphere and its rings


INTRODUCTION: Past remote observations of Saturn by Pioneer 11, Voyager 1 and 2, Earth-based observatories, and the Cassini prime and solstice missions suggested an inflow of water from the rings to the atmosphere. This would modify the chemistry of Saturn’s upper atmosphere and ionosphere. In situ observations during the Cassini Grand Finale provided an opportunity to study this chemical interaction.

RATIONALE: The Cassini Grand Finale consisted of 22 orbital revolutions (revs), with the closest approach to Saturn between the inner D ring and the equatorial atmosphere. The Cassini Ion Neutral Mass Spectrometer (INMS) measured the composition of Saturn’s upper atmosphere and its chemical interactions with material originating in the rings.

RESULTS: Molecular hydrogen was the most abundant constituent at all altitudes sampled. Analysis of the atmospheric structure of H₂ indicates a scale height with a temperature of 340 ± 20 K below 4000 km, at the altitudes and near-equatorial latitudes sampled by INMS.

Water inflall from the rings was observed, along with substantial amounts of methane, ammonia, molecular nitrogen, carbon monoxide, carbon dioxide, and impact fragments of organic nanoparticles. The infall mass flux was calculated to be between 4800 and 45,000 kg s⁻¹ in a latitude band of 8° near the equator.

The interpretation of this spectrum is complicated by the Cassini spacecraft’s high velocity of 31 km s⁻¹ relative to Saturn’s atmosphere. At this speed, molecules and particles have 5 eV per nucleon of energy and could have fragmented upon impact within the INMS antechamber of the closed ion source. As a result, the many organic compounds detected by INMS are very likely fragments of larger nanoparticles.

Evidence from INMS indicates the presence of molecular volatiles and organic fragments in the infalling material. Methane, carbon monoxide, and nitrogen make up the volatile inflow, whereas ammonia, water, carbon dioxide, and organic compound fragments are attributed to fragmentation inside the instrument’s antechamber of icy, organic-rich grains. The observations also show evidence for orbit-to-orbit variations in the mixing ratios of infalling material; this suggests that the source region of the material is temporally and/or longitudinally variable, possibly corresponding to localized source regions in the D ring.

CONCLUSION: The large mass of infalling material has implications for ring evolution, likely requiring transfer of material from the C ring to the D ring in a repeatable manner. The infalling material can affect the atmospheric chemistry and the carbon content of Saturn’s ionosphere and atmosphere.

INMS mass spectra from the Grand Finale. The graphic depicts the Cassini spacecraft as it passes from north to south between Saturn and its rings. The inset spectrum shows the mass deconvolution of compounds measured by INMS on rev 290. The x axis is in units of mass per charge (u) and extends over the full mass range of INMS (1 to 99 u). The y axis is in counts per measurement cycle integrated over the closest-approach data. The mass influx rate for rev 290, derived from mass deconvolution of the rev-integrated spectrum, is shown as embedded text in the spectrum. The side panel gives the average of the mass deconvolution of revs 290, 291, and 292 in mass density units (g cm⁻³). The composition of the ring-derived compounds in terms of percentage mass density is also shown.
The Pioneer and Voyager spacecraft made close-up measurements of Saturn’s ionosphere and upper atmosphere in the 1970s and 1980s that suggested a chemical interaction between the rings and atmosphere. Exploring this interaction provides information on ring composition and the influence on Saturn’s atmosphere from infalling material. The Cassini Ion Neutral Mass Spectrometer sampled in situ the region between the D ring and Saturn during the spacecraft’s Grand Finale phase. We used these measurements to characterize the atmospheric structure and material influx from the rings. The atmospheric He/H$_2$ ratio is 10 to 16%. Volatile compounds from the rings (methylene; carbon monoxide and/or molecular nitrogen), as well as larger organic-bearing grains, are flowing inward at a rate of 4800 to 45,000 kilograms per second.

Early modeling of Saturn’s atmosphere/ionosphere coupling (I) prior to the first radio occultation measurements by Pioneer 11 adopted compositional constraints from Earth-based observations of the well-mixed saturnian atmosphere and used a range of values of the turbulent mixing and heating of the atmosphere based on past planetary observations. Depending on the chosen thermal profile and strength of turbulent mixing, a range of atmospheric and ionospheric conditions were deemed possible (I). The “nominal” model of the ionosphere predicted that protons were the primary ion and that the proton’s slow radiative recombination reaction was the primary chemical loss pathway, indicating a density of the ionosphere reaching $10^5$ cm$^{-3}$. The modeling suggested that ionospheric composition and structure could serve as a diagnostic of the composition, thermal structure, and turbulent mixing of the upper atmosphere. However, the first radio occultation measurements of the ionosphere made by Pioneer 11 on 1 September 1979 found a peak electron density an order of magnitude lower than predicted for moderate eddy mixing and a warm thermosphere (2). The discrepancy was not well understood at the time.

Voyager radio occultation measurements (3) supported the low peak ionospheric density and provided independent evidence that the low peak ionospheric density extended into the night side (4). It was suggested (5, 6) that water from the rings flowing into the atmosphere could chemically convert protons to molecular H$_2$O$^+$ ions at a rate that reproduced the peak electron densities observed by Pioneer and Voyager. The globally averaged water influx rate was estimated to be $4 \times 10^8$ cm$^{-2}$ s$^{-1}$, with localized influx as high as $2 \times 10^9$ cm$^{-2}$ s$^{-1}$ (6). This proposal of water influx was bolstered by further modeling (7, 8) and ground-based observations of H$_2$ in the Saturn ionosphere (9).

The 59 Cassini radio occultations carried out over the course of its prime and solstice missions provided additional data on the ionospheric structure (8, 10). Low latitudes—within 20$^\circ$ of the equator—have lower ionospheric density. Water influx from the rings is a strong candidate to explain the observed latitudinal variations; modeling (8) indicates that water influx with a Gaussian distribution about the equator and a peak flux of $5 \times 10^8$ cm$^{-2}$ s$^{-1}$ can match the observations obtained prior to the Grand Finale time period.

**Observations during the Cassini Grand Finale**

The Grand Finale phase of the Cassini mission began on 22 April 2017 with a final close flyby of Titan that diverted the spacecraft to fly 22 times between the planet and its rings. The mission ended on 15 September 2017 after another gravitational deflection by Titan that sent the spacecraft plunging into Saturn’s dense atmosphere. Cassini’s trajectory between the innermost D ring and the planet allowed in situ coverage of the equatorial ring-atmosphere interaction. Flybys varied in altitude between 1360 and 4600 km above the atmosphere’s 1-bar pressure level in three groups (Fig. 1).

The Grand Finale objectives included measuring Saturn’s atmospheric H$_2$ and He and searching for compounds such as water that might indicate an interaction of the upper atmosphere with the main rings. The Ion Neutral Mass Spectrometer (INMS) (11) measurements were made several hundred kilometers above the homopause, the level at which turbulent or eddy mixing and molecular diffusion are equal (Fig. 1). In this region, molecular diffusion produces a mass-dependent separation: Lighter compounds have a larger vertical extent due to Saturn’s gravity. Prior to the Grand Finale, models and occultation data (12, 13) suggested that H$_2$, He, and HD were the only neutrals in the upper atmosphere that would be measurable by INMS. The heavier molecule methane was predicted to be present at the -0.1% level in the well-mixed lower atmosphere (below 1000 km; Fig. 1), but below the detection limits of INMS at the high altitudes sampled by Cassini (12, 13).

**Atmospheric composition**

INMS obtained measurements of neutral molecules using the Closed Source Neutral (CSN) mode (17). INMS operated in a survey mode, acquiring mass spectral data at every mass within its range [1 to 99 atomic mass units (u)] at resolution of 1 u, with a repetition rate of 9.5 s (~300 km along track) or 4.5 s (~150 km) when ionospheric data were or were not being acquired sequentially, respectively.

Figure 1 indicates the three altitude regions between the atmosphere and the rings where measurements were made by INMS. Figure 2 shows data for the major atmospheric components H$_2$, HD, and HD + He, separated into those three altitude bands. HD and He have the same atomic mass, so they cannot be measured separately. Because of the geometry of the orbit (rev) for each altitude region, there is a strong correlation between altitude and latitude. The closest approach to Saturn occurred at 4$^\circ$ to 6$^\circ$S and not at the equator. This allowed us to determine whether the observed compounds are better correlated with a neutral flux from the rings or with Saturn’s atmospheric structure (see below). All orbits occurred near local solar noon. This geometry provides complementary

---

**Note:** This excerpt is from a scientific article discussing the chemical interactions between Saturn’s atmosphere and its rings, focusing on the Cassini mission’s observations and measurements. It highlights the challenges of modeling and the importance of in situ data for understanding the complex interactions between Saturn’s rings and its atmosphere.
information to the Pioneer, Voyager, and Cassini radio occultations, which probed near the dusk and dawn terminators. The Cassini orbits covered a range of Saturn rotational longitudes (Fig. 2). For the low-altitude observations (Fig. 2C), the differences in the shape of the H$_2$, HD + $^3$He, and $^4$He altitude profiles are due to changes in their respective abundances and indicate the effects of diffusive separation via gravity.

H$_2$ and He data were examined to determine the variability due to altitude, latitude, and orbit, the latter representing temporal and/or longitudinal effects. For each orbit, raw count data were converted to densities (14) and an average altitude and density were calculated every 5° latitude using the 11 data points closest in latitude (Fig. 3). Local scale heights were then fitted at each latitude from surrounding data having densities within a factor of $1/(2e)$ higher or lower than the average density, one e-fold about on the latitude of interest. In addition to local scale heights, a common scale height was calculated using data across all observed altitudes, latitudes, and revs. This was facilitated because altitude and latitude are highly correlated and do not vary much from one orbit to the next. With the exception of 5°N latitude, all altitude/latitude bins are consistent with this common scale height ($H$), given by $H = kT/(mg)$, where $k$ is Boltzmann’s constant, $T$ is the H$_2$ gas temperature, $g$ is the local acceleration due to gravity, and $m$ is the mass of the gas molecule, H$_2$ in this case. The common scale height represented in Fig. 3 corresponds to a temperature of $340 \pm 20$ K. The slopes of the local scale height at 5°N are steeper than the common scale height fit, suggesting a higher temperature. The scale height correspondence between the various altitudes/latitudes sampled, the times/longitudes sampled (on the different revs), and the locally determined scale heights calculated at each point show little evidence for major temporal or spatial atmospheric variation in the region sampled by Cassini during the Grand Finale (15).

The analysis of the INMS measurements indicates an atmosphere that has a more complex mass spectrum than predicted by models. There is evidence for both volatile compounds and fragments derived from nanograin impacts in the INMS antechamber. We conclude that the nanograins are sourced from the ring plane. Figure 4 shows the latitude distributions of mass 15 u and mass 28 u in the three distinct altitude ranges. Mass 15 u is the CH$_3^+$ fragment of methane (mass 16 u is not used because of interference from mass 16 oxygen from water electron impact dissociative ionization), whereas mass 28 u may be derived from N$_2$, CO, and/or C$_2$H$_4$. Mass deconvolution for revs 290, 291, and 292 indicates that less than 10% of the 15 u peak is derived from dissociative fragments from ammonia or heavy organics. From deconvolution of these same spectra, we attribute the fractional contributions of the 28 u signal to be 28% to 58% (average 45%) CO, 41% to 50% (average 46%) N$_2$, and 0% to 26% (average 9%) C$_2$H$_4$ an organic formed from fragmentation of nanograins.

Discrimination between volatile and nanograin-derived signals is achieved by comparing the data in Fig. 4 at the three separate altitude ranges. The uppermost altitude range shows that both mass 28 u and mass 15 u reach a maximum abundance at the equator rather than at the closest approach latitude (~5°S) with a very large spike for mass 28 u at the equator, which we attribute to the C$_2$H$_4$ portion of the peak. The broad latitude extent of the distributions indicates a distributed volatile source in the ring plane. The mass 28 u signal is consistent with C$_2$H$_4$ derived from nanograins that have a very narrow Gaussian distribution peaked within 1° of the ring plane at this altitude (~3500 km), comparable to the nanograin distribution seen by the Magnetospheric Imaging Instrument (MIMI) investigation (16).

---

**Table 1. Mass influx values and composition of inflowing ring material.** Density and composition values are the average of revs 290, 291, and 292.

<table>
<thead>
<tr>
<th>Source</th>
<th>Density</th>
<th>Mass influx (kg s$^{-1}$)</th>
<th>Source composition (mass fraction ± 1σ uncertainty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturn’s atmosphere</td>
<td>4.7 $\times$ 10$^{-15}$ g cm$^{-3}$</td>
<td>Hydrogen: 99.95 ± 0.01% Helium: 0.05 ± 0.01%</td>
<td></td>
</tr>
<tr>
<td>Inflowing ring material</td>
<td>1.6 $\times$ 10$^{-16}$ g cm$^{-3}$</td>
<td>Methane: 16 ± 3% Ammonia: 2.4 ± 0.5% Water: 24 ± 5% CO/N$_2$: 20 ± 3% Carbon dioxide: 0.5 ± 0.1% Organics: 37 ± 5%</td>
<td></td>
</tr>
</tbody>
</table>

---
Both the mass 15 u and mass 28 u compounds also have a component that has begun to spread in latitude toward the closest-approach latitude (4° to 6°S) even at the highest altitudes measured. This is more obvious for mass 15 u than for mass 28 u. This spreading indicates that collisions between the volatile ring components and the saturnian atmosphere (H₂ and He) are beginning to "diffusively couple" the volatiles into the atmosphere as they flow from the rings. At the measured atmospheric densities for this altitude range, diffusive coupling can only occur with molecular volatiles and not heavier nanograins. The latter undergo a smaller relative momentum exchange with the predominantly light hydrogen atmosphere. In the lower-altitude bands, the equatorial peaks disappear as both volatiles and nanograins are diffusively coupled into the atmosphere at the correspondingly higher atmospheric densities. This can be seen for the lower-altitude bands as

---

**Fig. 2. Major atmospheric gases observed by INMS.** The measured densities (points, with shading representing the 1σ uncertainty) of H₂, ³He, and HD + ³He are shown along the spacecraft trajectory for all INMS observations during the Grand Finale. (A to C) Data are grouped into the three altitude bands denoted in Fig. 1. The signal-to-noise ratios for the highest two altitude bands are too low to allow measurement of He or HD + ³He. The latitude is indicated on the lower axis, and closest approach is denoted by the vertical dotted lines. The spacecraft altitudes above the 1-bar pressure level are shown by the gray curves. The spacecraft moves from right to left in each plot. The corotation longitude and rev number are shown in the upper left and upper right corner of each plot, respectively. The final plunge into the atmosphere is labeled; the telemetry from the spacecraft ended at ~1360 km above the 1-bar pressure level.
the peak distributions of masses 28 u and 15 u shift into alignment with the closest-approach latitude near 5°S. The lowest-altitude band shows symmetric distributions of masses 15 u and 28 u. Their variation with latitude and altitude indicates that masses 15 u and 28 u are dominated by diffusive interaction with the H₂ atmosphere and are free-falling at a terminal velocity, dictated by the increasing hydrogen density and its slowing of the gas. Thus, as the altitude decreases and the background atmosphere increases in density, the maximum diffusion velocity decreases and the infalling material density increases to maintain flux continuity (apart from small effects at this altitude due to chemical loss and latitudinal spreading). This process allows us to estimate the diffusion velocity and determine the material’s influx rate from the measured densities (see below).

Figure 4D reinforces the interpretation that the observed compounds originated in the rings. It indicates that for mass 15 u (CH₄ from methane), mass 28 u (CO, N₂, and C₂H₆), mass 44 u (CO₂ and propane), and a surrogate heavier mass from nanograin fragments at 78 u (benzene), the relative abundances are highest at the highest altitudes and reach a near-constant relative abundance below 2500 km as the material is diffusively coupled into Saturn’s atmosphere.

Although the solar local time does not vary, the Saturn longitude does change from one orbit to the next. The abundance and distribution of methane, one of the major influx volatiles, varies by a factor of 3 about the average abundance (Fig. 4D, lowest-altitude values). These orbit-to-orbit variations indicate a spatial or temporal change of the volatile source on time scales that are faster than the horizontal diffusion time scale. However, there is no simple variability associated with Saturn’s corotational longitude. There is a tentative link to longitudinal variations in the D68 ringlet near the inner edge of the D ring, in which a series of bright clumps appeared in 2015 (Fig. 5). An influx that is spatially concentrated near the clumps may in part explain the spatial and/or temporal variations.

**Impact fragmentation**

The inflowing ring material impacted the INMS antechamber at 29 to 31 km s⁻¹ (five times the speeds for which INMS was designed), leading to uncertainty in both absolute abundances and identification of the molecular species. At 31 km s⁻¹, molecules and nanoparticles carry 5 eV of kinetic energy for each atomic mass unit, which in some cases would have been sufficient to dissociate incoming particles and molecules as they impacted the CSN antechamber. However, studies of surface-induced dissociation (e.g., (18)) indicate that only about 25% of the impact energy is converted to internal energy of the molecule in the collision process. For H₂ this translates into ~2.5 eV, which is below its dissociation energy of 4.75 eV. Laboratory studies of dissociation in molecule-surface collisions (19) suggest that the interaction of H₂ with passive surfaces such as Ag proceeds as a direct interaction with surface atoms. These atomic interactions have a strong angular dependence, with a 10-eV neutral beam having a probability of dissociation of 50% for collinear collisions and >50% for perpendicular collisions. Interaction with a raw Ti surface, such as the CSN antechamber wall after fresh material is exposed through a grain impact, can lead to chemical adsorption (chemisorption) that produces metal hydrides (20). Chemisorption processes can also play a role with active metal surfaces or with oxygen-bearing compounds. Therefore, for H₂, CH₄, NH₃, and N₂, the effects of chemisorption in the fragmentation are likely moderate in our case, whereas for H₂O, CO, and CO₂, chemisorption/fragmentation will likely affect our measurements. For example, some of the CO observed at mass 28 u may be an impact fragment from CO₂, which does not affect our main conclusions. Impact fragmentation of CH₄ to produce CH₃ will likely result in reformation of CH₄ on the surface due to the high content and rapid movement of H radicals on the surface in this hydrogen-rich environment. Similarly, CH₃ terminal groups from larger organics may also add to the methane signature, but because heavy organic compounds are at least an order of magnitude less abundant, this can increase the derived CH₄ value by at most 10%. Furthermore, this increase will be compensated by a decrease as a result of CH₂ impact fragmentation that forms CH and CH₂ fragments, which are lost from the antechamber before they can pick up two hydrogens in separate surface reactions because the surface coverage is relatively low (<30%). The net result is that we expect that the CH₄ statistical uncertainty encompasses the additional systematic uncertainties from various fragmentation processes.

The possibility of particle fragmentation inside the closed source does not affect our main conclusions about Saturn’s atmospheric structure. With regard to H₂, the agreement of the outbound and inbound data for each orbit examined (290, 291, and 292) below 3000 km and the common scale heights observed at all altitudes, latitudes,
and orbits (Fig. 3A) indicate that the effects of dissociation are limited and do not affect the derived atmospheric structure below 3500 km. However, \( \text{H}_2 \) densities of \( 10^6 \, \text{cm}^{-3} \) in an extended outbound region above 4000 km have a constant slope (with density decreasing versus time and altitude) that tracks with the decay of water, which is known to adsorb to the instrument walls \( (21) \). This correlation suggests that grains have sputtered some raw \( \text{Ti} \) into the antechamber, allowing hydride formation on the antechamber surface. This hydrogen may have been subsequently displaced by the oxygen from water molecules (\( \text{TiO} \) and \( \text{TiO}_2 \) are more tightly bound than the metal hydride) clinging to the antechamber walls after the flyby, thereby creating a low level of \( \text{H}_2 \) production. This precludes the use of values for \( \text{H}_2 \) on the outbound phase above 4000 km, but does not affect our other results. However, the loss of water reacting with \( \text{Ti} \) vapor does suggest that the water abundance may be as

---

**Fig. 4. Volatile inflow from the rings.** (A to C) Plots of latitude and altitude relative to 1 bar for the 15 u and 28 u mass spectral features [in counts per 31-ms integration period (IP) with 1\( \sigma \) uncertainty as colored shading] averaged over each altitude band. The mass 2 u counts (scaled to match the 28 u peak value) are also provided for reference. The high-altitude band comprises revs 278 to 280 (A); the mid-altitude band, revs 271, 273 to 275, 283, 284, 286, and 287 (B); and the lowest-altitude band, revs 288 to 292 (C). The distributions shift in latitude from 0° to closest approach (~5°S) as altitudes decrease. The mass 28 u feature in the highest-altitude bin has both a broad latitude feature, like the 15 u feature, and a sharp spike at the equator indicating contributions from both volatiles (\( \text{CO} \) and/or \( \text{N}_2 \)) and grains (\( \text{C}_2\text{H}_4 \) fragments from organic grain impacts). (D) Abundances (with 1\( \sigma \) error bars) for 28 u (carbon monoxide, molecular nitrogen, and ethylene), 15 u (methane), 44 u (carbon dioxide plus a propane impact fragment), and 78 u (a benzene impact fragment) as a function of altitude at the equator (squares) and at 5°S latitude (circles). The equatorial latitude is the location of ring plane influx, whereas 5°S latitude represents the closest approach to the atmosphere as a result of the flyby geometry (see Fig. 2).
much as 30% larger than reported in Table 1 and Fig. 6. Because the deuterium hydride has a lower activation barrier for formation than the H hydride (20), which led to H/D fractionation during the flyby, the present dataset is difficult to use for studying the H/D ratio of the atmosphere and rings.

The strongest evidence that CH₄ and N₂ are not simply by-products of fragmentation of heavy compounds, but instead native volatile gases, comes from the latitude distributions of mass 15 u and mass 28 u at the highest altitudes (3500 to 4000 km; see Fig. 4 and related text). The mass 15 u (methane) and mass 28 u signals both show a broad latitude distribution running from 20°S to 10°N latitude but differ in peak location; this finding constitutes evidence for a latitudinal spread of the native volatile compounds (CO and N₂), combined with C₂H₄ impact fragments of nanograins that this rough classification between native volatiles and fragments derived from nanograins.

Our assessment of the composition of the inflowing material observed on revs 290, 291, and 292 gives the following fractions by weight: methane, 16 ± 3%; ammonia, 24 ± 5%; water, 24 ± 5%; molecular nitrogen and carbon monoxide (CO/N₂), 20 ± 3%; carbon dioxide, 0.5 ± 0.1%; and organic compounds, 37 ± 5%. The values reported are the mean of the orbits analyzed. To account for physical adsorption (physisorption) and chemisorption to the instrument walls (21), we generated integrated spectra (Fig. 6). For masses with a high tendency to interact with the walls of the antechamber (those in rev 290 with a ratio of outbound to inbound counts greater than 2 at 1750 km and with a maximum count rate greater than 40), the integrated spectra show the integrated signal at each mass over the full time period for which the signal at 18 u is above the background level. The remaining masses are integrated using the time window from 500 s before to 500 s after closest approach. We used a standard fitting procedure (22). Using data from calibrations of the INMS engineering model and the National Institute of Standards and Technology mass spectral library (23) to determine the dissociative fragmentation patterns and absolute calibration, we constrain the abundances of carbon dioxide, CO/N₂, water, ammonia, methane, hydrogen, and helium for each integrated spectrum. The remaining counts at masses >12 u are attributed to organic species. Some signal may be due in part to inorganic S-bearing species such as H₂S or SO₂; however, the overall abundance of these compounds is consistently <0.1% by mass of the inflowing material and less than our quoted uncertainties.

The ring particle composition (i.e., compounds other than H₂ and He) is approximately 37 weight percent (wt %) organic compounds heavier than CH₄. The other abundant ring particle compounds are water, CO/N₂, methane, ammonia, and carbon dioxide. Signals at 12 u and 14 u constrain the abundances of CO and N₂, respectively, and suggest that an inorganic component is likely present at 28 u. However, the value for CO reported is an upper limit, as the constraint from 12 u does not account for ionization fragments from organics or from impact fragmentation of CO₂ internal to the instrument. The organic fraction itself is fitted well by hydrocarbons, but the
the order of $10^{12}$ is equivalent to the mass of $\sim 10^6$ cm$^{-3}$

spectra suggest abundant native organic materials. In either case, these compounds with masses in the range detected by MIMI ($\mu$-16) are comprised $\sim$5 to 10 wt % of organics. Aromatic species, including the possible signal of benzene at $\mu$-78, we estimate that the total organic mass density is on the order of $10^{10}$ g cm$^{-3}$. The organic compounds identified may be either indigenous compounds present in the atmosphere or the products of high-speed impacts with INMS (see above). In either case, these spectra suggest abundant native organic material. The mass of hydrocarbons detected by INMS is equivalent to the mass of $10^9$ cm$^{-3}$ nanoparticles with masses in the range detected by MIMI (24). Because MIMI detected far fewer particles, most of the mass measured by INMS appears to be below the 9000 u lower measurement limit of MIMI (24).

Masses above $\sim 70$ u are poorly fit by compounds with primary masses in the range of INMS. Because studies of heavy extraterrestrial organics indicate that these heavier organic compounds include aromatics (e.g., (25)), common aromatic molecules such as naphthalene were added to the spectral library as candidate parent species for this region. Compounds produced by ion irradiation experiments (26, 27) were also considered. We find that this mass region is consistent with the presence of aromatic compounds comprising $\sim$5 to 10 wt % of organics. Aromatic material would be subject to impact dissociation that may yield aliphatic compounds, so this abundance of aromatic material is a lower limit.

**Estimating the mass influx in the equatorial region**

We estimated the mass influx of material in the equatorial region by combining calculations of the material velocities and densities. From the mass deconvolution described above, we estimated the densities of methane, water, ammonia, nitrogen, carbon monoxide, carbon dioxide, and organic fragments measured at an altitude of 2000 km during revs 290, 291, and 292 (see Fig. 6). We used two different approaches to determine the appropriate downward diffusion velocity. One is based on the limiting flux equation (28):

$$v = \frac{D_2}{H} \left(1 - \frac{m_2}{m}\right)$$

where $H$ is the scale height (we use a value of 150 km based on the INMS data), $m$ is the mass of the minor species of interest, and $m_2$ is the mean mass of the atmosphere (we use a value of 2 u). $D_2$ is the coefficient for diffusion of species 1 in species 2. The alternative approach uses the diffusion coefficients calculated using a simple hydrostatic model adapted from previous work (29). The methane diffusion velocity at 2000 km is calculated using both methods for a range of influx values of methane. The maximum ($1 \times 10^4$ cm s$^{-1}$) and minimum ($4.5 \times 10^3$ cm s$^{-1}$) diffusion velocities are then taken as bounding cases. The diffusion velocities for the other materials are scaled by the ratio to methane of their diffusion coefficients flowing through H$_2$ (30). The range of diffusion velocities used in this calculation is inclusive enough that assumptions about whether methane, ammonia, water, nitrogen, carbon monoxide, and carbon dioxide are present at 2000 km as volatiles or are derived as fragments of a larger organic moiety will have little effect on the diffusion velocity calculation. The equatorial latitude band used in the mass influx calculation is 8° wide, which is the half width of the low-altitude measurements in Fig. 4C. The difference between the maximum and minimum values is completely dominated by the uncertainty of determining the diffusion velocities, which is a systematic uncertainty that is constant from one orbit to the next. The uncertainty due to the densities of the components is $\sim$1%, indicating that there is variation in the mass influx between rev 291 and the other two revs (290 and 292) we analyzed. However, the mass fraction of a given component is not statistically different from orbit to orbit. Calculated mass influx rates for revs 290, 291, and 292 and the average composition of material from Saturn’s atmosphere and from ring influx are reported in Table 1 and Fig. 6.

**Ionospheric measurements**

The open source on the Cassini INMS was designed with the primary purpose of measuring
reactive neutrals and ambient ions in Titan’s ionosphere and upper atmosphere (11), where flyby velocities were in the range of 6 km s⁻¹. However, the Cassini Grand Finale orbits resulted in spacecraft speeds relative to the atmosphere of ≈31 km s⁻¹. At these speeds, INMS ion measurements were limited to < 8 u. Despite the limited mass range, INMS measurements of light ions can be combined with Radio Plasma Wave Spectrometer (RPWS) measurements of the free electron content (31, 32) to produce a more complete picture of the ionosphere. The INMS open source has a narrow field of view (< 2° cone) relative to the closed source (180° cone). Therefore, the spacecraft must be used to point the instrument into the ram direction to allow measurements of ions. This orientation occurred on a limited set of Grand Finale revs (283, 287, 288, and 292).

Figure 7 shows the ionospheric data obtained by INMS during the Cassini Grand Finale. Figure 7, A and B, shows the mid-altitude band (revs 283 and 287; refer to Fig. 1 for context). These time series indicate that for the altitudes and latitudes covered by these orbits, the free electron density is within a factor of 2 of the INMS measured light ion density. The asymmetry between north and south latitudes above 15° can be attributed to ring shadow effects during the autumnal solstice illumination (33). This reduces incoming solar ultraviolet flux, lowering the photoionization, although the effect is somewhat mitigated by the long lifetimes of the H⁺ and H₃⁺ ions and the associated transport effects. Figure 7, C and D, shows revs 288 and 292 from the lowest set of altitudes, where the near-equatorial ionosphere shows a large difference between the free electron density and the light ion density, indicating the presence of heavier ions (> 8 u) that must account for the bulk of the ionospheric density (more than 75% of the ions are > 8 u). This heavy-ion region is asymmetric with respect to the equator, ranging in latitude from 2°N to 12°S. However, it does roughly correlate with the inflow of volatiles and organic nanograins from the D ring discussed above, and closely matches MIMI Charge Energy Mass Spectrometer (CHEMS) measurements of nanoparticles (36). The molecular volatiles (water, methane, ammonia, carbon dioxide) can easily convert the long-lived protons of the ionosphere into molecular ions with shorter lifetimes, decreasing the overall electron density (5), as described below.

Figure 7E shows additional measurements of the ionosphere for rev 288. The individual light ion concentrations for H⁺, H₂⁺, H₃⁺, and He⁺ are indicated. The H⁺ and H₂⁺ densities decrease in the near-equatorial heavy-ion region, consistent with an inflow of heavier molecules. The H₂⁺ ions measured are the primary product of ionization in the Saturn ionosphere and are created by ionization of H₂, the most abundant neutral, by solar extreme ultraviolet radiation (34). They are a good tracer of the ionization process. Figure 7E also shows the scaled value of the positive nanoparticles measured by CHEMS (36) added to the INMS light ion density. The second-order latitudinal structure of the CHEMS measurements of positive nanoparticles is closely correlated with the free electron density of the bulk ionosphere. Although the scaling factor is ~10⁶ and these very large positive ions cannot themselves account for the secondary structure, they represent the positive member of a dusty plasma that contains both neutral nanoparticles and negative-ion nanoparticles, which appears to affect the recombination of the primary positive molecular ions that dominate the equatorial ionosphere.
Implications for Saturn’s atmosphere
and ionosphere

**Atmospheric structure**

The analyses shown in Figs. 2 and 3 indicate a background atmospheric structure that is consistent with predictions shown in Fig. 1 for both hydrogen and helium. However, species heavier than helium are far more abundant than predicted. The differences between the predicted and observed structure are largely confined to the excess volatiles that we have concluded and observed atmosphere are largely confined to the excess volatiles that we have concluded.

The measured hydrogen and helium abundances are compared to the models (35) in Fig. 8. The vertical profiles of the helium and methane abundances calculated by the hydrostatic model (29), which was used to benchmark the nonhydrostatic Global Ionosphere-Thermosphere Model (36, 37), are shown. Methane abundances for altitudes below those observed by INMS are taken from the combination of Cassini Ultraviolet Imaging Spectrograph (UVIS) and Composite Infrared Spectrometer (CIRS) data (35). As can be seen in Fig. 8, the relatively large uncertainties in the methane abundance allow both approaches to reproduce the UVIS/CIRS methane data equivalently well, even though they use widely different versions of the eddy diffusion coefficient.

Also shown in Fig. 8 are two different scenarios for the deep-atmosphere He/H₂ ratio. The purple curves adopt a He/H₂ ratio of 0.03, consistent with a helium abundance of ~0.0291 reported from the Voyager measurements (38). We use the ratio of 0.03 to represent the most likely lower bound for the well-mixed atmosphere value for helium (35). The other set of helium curves represent a He/H₂ ratio in the well-mixed lower-altitude region of the atmosphere of ~0.16, an abundance of helium of ~0.1355; this value is more consistent with the recent analysis (35), which reports a homosphere abundance of ~0.11 ± 0.02 inferred from UVIS and CIRS data. The latter approach brackets the helium abundances obtained directly from the INMS measurements, whereas the Voyager-derived curves systematically fall below the data (Fig. 8). This comparison suggests that the INMS helium data are more consistent with a nearly jovian homosphere abundance of ~0.1355 (39). In contrast, the model that uses a lower He/H₂ ratio systematically fails to reproduce the INMS data (15). These results for the homospheric ratio of He/H₂ have implications for understanding the internal structure and evolution of Saturn. The conventional explanation for the excess infrared luminosity of Saturn relative to the expected thermal emission is that cooling over time leads to the demixing of helium from hydrogen, with the heavier helium raining out into the deeper interior and generating heat (40). Our measurements and modeling permit a modest depletion of helium but are inconsistent with a strong depletion relative to the protosolar He/H₂ ratio of 0.19 (41). As an example, the nominal INMS value for the He/H₂ ratio is 0.16 (Fig. 8), which is similar to the value at Jupiter (0.157 ± 0.003) (42). However, some additional helium rain in Saturn beyond that in Jupiter is allowed, as the INMS data are consistent with a He/H₂ ratio as low as 0.10. A range between 0.10 and 0.16 would maintain the viability of helium—a process that is consistent with He/H₂ < 0.12 in the well-mixed atmosphere (43)—as the cause of excess luminosity. This range is also consistent with the most recently derived He/H₂ ratio of 0.11 to 0.16 from Voyager (44) and with the Cassini UVIS-CIRS value of 0.09 to 0.13 (35). Overall, the homospheric helium abundance from INMS may be slightly higher than previous estimates, but the uncertainties are large.

**Ionospheric structure**

The presence of the light-ion species observed by INMS in the ionosphere (H⁺, H₂⁺, H₃⁺, He⁺) was predicted almost 40 years ago by a model of a neutral atmosphere dominated by H₂ and He (7). Ion and neutral measurements made by INMS in the ionosphere are consistent in that they both indicate the presence of an additional heavy molecular species (both neutral and ionized) in the equatorial upper atmosphere. Water-group neutral and ion species were predicted, but the present Cassini data indicate that the chemical composition of the material falling inward from the rings is concentrated at the equator, is chemically much more complex than predicted, and includes a substantial organic component, perhaps in the form of nanoparticles.

Dissociative and nondissociative photoionization of molecular hydrogen (and to a lesser degree He) by solar extreme ultraviolet radiation is the source of ionization in the equatorial ionosphere. The H₂⁺ and H⁺ ions thus produced undergo a series of ion-neutral reactions, generating other ion species such as H⁺ via the fast reaction H₂⁺ + H₂ → H₃⁺ + H. The H₃⁺ production rate along the spacecraft track can be determined empirically by multiplying the measured H₃⁺ density by the measured H₂ density (both shown for rev 288 in Fig. 7E) and by the rate coefficient of 2 × 10⁻⁹ cm³ s⁻¹ (34). The production rate is ~8 cm⁻³ s⁻¹ near closest approach. At these altitudes, the effects of approximately 50% opacity in the extreme ultraviolet are evident in the production rate, indicating that the spacecraft’s closest approach nearly reached the altitude of peak ion production. This effect is also evident as the dip near closest approach in the H₃⁺ densities in Fig. 7.

Figure 7E also shows a broad gap near closest approach between the total light-ion densities measured by INMS and the electron densities measured by RPWS. Assuming quasi-neutrality (that is, the ion density approximately equals the electron density) and neglecting negative ions, this suggests the existence of an ion with a mass beyond the upper limit of the open source for these orbits (8 u). This ion, or collection of ions, is more abundant than light ions in the

---

**References**: Waite et al., Science 362, eaat2382 (2018)
main ionospheric layer. To maintain consistency with the neutral composition provided by the closed source, the heavy ion cannot be solely a water-derived molecular ion. Simple ion chemistry for the light ions can put limits on the abundance of the heavy neutral ring ions with a large dissociative recombination rate coefficient. The low H\(^+\) and H\(_2\)\(^+\) densities measured near closest approach require fast reactions with a molecular volatile at an abundance of approximately 10^{-3} (34), consistent with the INMS neutral data. This simple ion analysis does not indicate the identity of the molecular volatile, which likely includes methane, ammonia, water, and carbon dioxide as measured by INMS. These compositional changes are discussed in (45).

Simple photochemistry for a single major ion (i.e., H\(_2\)\(^+\)) states that the total ion production rate equals the ion-electron loss rate from dissociative recombination. This leads to an expression for the electron density \(N_e\):

\[
N_e = \left( \frac{P_{H_2^+}}{\alpha} \right)^{1/3}
\]

(2)

where \(P_{H_2^+}\) is the H\(_2\)\(^+\) production rate and \(\alpha = 5 \times 10^{-7} \text{ cm}^3 \text{ s}^{-1}\) is a typical dissociative recombination rate coefficient (46). Using the peak production rate near closest approach from Fig. 7 yields a photochemical equilibrium value of \(N_e \approx 10^{10} \text{ cm}^{-3}\), in good agreement with the peak electron density measured by RPWS (31, 32). This agreement suggests that the role of negative ions and/or particles in determining the charge balance may be relatively minor.

It is well known in planetary and terrestrial aeronomy (47) that chemistry dominates at lower altitudes in an ionosphere, whereas transport processes become important at higher altitudes where the collision frequency is low. We expect this to be true for Saturn's ionosphere as well. The chemical lifetime of the major molecular compounds varies from \(-200\) s near closest approach up to \(-2000\) s (i.e., about 30 min) near the upper edge of the heavy-ion gap/layer. The H\(^+\) chemical lifetime should be controlled by the abundance of the heavy neutral compounds, which increases rapidly with altitude, via ion-neutral reactions. Plasma transport is largely constrained to proceed along the magnetic field (47), which in the equatorial region is almost horizontal. The H\(_2\)\(^+\) production rate sharply falls off by a factor of \(-10\) in the shadow of the planet's B ring (Fig. 7E), and the H\(_2\)\(^+\) density also falls off rapidly. However, the H\(_2\)\(^+\) density, which is equivalent to \(N_e\) in this region, falls more slowly. This suggests that H\(^+\) is not in chemical equilibrium in the altitude region near 2000 km and above, but that H\(_2\)\(^+\) plasma is produced outside this region and flows into the shadowed area.

He\(^+\) ions (4\(\alpha\)) are created by the photionization of atmospheric He, which falls with altitude more rapidly than H\(_2\) because of diffusive separation. Figure 7E shows that the He\(^+\) density decreases more rapidly with altitude than does the H\(_2\)\(^+\) density. However, some of the 4\(\alpha\) signal is contributed by H\(_2\)D\(^+\).

**Origin of volatiles in the thermosphere**

Molecular hydrogen and helium, which are sourced from the well-mixed atmosphere via diffusive transport, are the most abundant neutral species in the upper atmosphere of Saturn. The next most abundant category of neutrals by mass is organics, followed by water, mass 28 u inorganics (CO and N\(_2\)), and methane (Fig. 6). Methane is too heavy to diffuse upward from the homosphere, so the source of methane must be external (see above). The source of CH\(_4\) seems to be Saturn's rings. One possibility is that an icy carrier of CH\(_4\) (e.g., clathrate hydrate) may be present inside the ring particles, which volatilizes when heated by sunlight or ablation in Saturn's thermosphere. Any CH\(_4\) gas released would diffuse into Saturn's atmosphere under gravity.

The volatile composition observed by INMS appears to be similar to material found in comets (49). This could be explained if Saturn's rings were formed from unprocessed primordial ices, derived from a thermally primitive precursor body such as a small icy moon. Alternatively, the similarity may be coincidental if species such as CH\(_4\), NH\(_3\), and CO are major products of the thermal/ultraviolet degradation of complex organics in an H\(_2\)-rich environment.

The mass of Saturn's C ring is \(-10^{18}\) kg (49), about 0.03 times the mass of Saturn's moon Mimas. Therefore, if we use the mass influx inferred from the INMS measurements (4800 to 45000 kg s\(^{-1}\)), we calculate a lifetime of 70000 to 7 million years for the C ring. Yet this only reflects today's influx. The current influx is directly from the D ring rather than the C ring, which must be the ultimate supplier because the mass of the D ring (likely no more than 1% of the C ring mass (50)) can maintain current loss rates for only 7000 to 66,000 years—a very short amount of time in terms of solar history. It is unclear whether the C ring can lose 1% of its mass into the D ring by viscous spreading over that time period (51).

Although viscous spreading of the C ring is likely not the cause of mass transfer to the D ring (51), occasional transfer of \(-1%\) of the mass of the C ring into the D ring region via a large ring-tilting event is feasible. These ring-tilting events involve a stream of planet-orbiting rubble crossing the ring plane somewhere in the C or D rings. The C ring provides the ultimate source, containing enough mass to last (at current influx rates) about 5% of the time that the rings themselves have existed (~200 million years) (52-54).

The D ring could be repopulated sporadically by large impact events such as those that tilted the D and C ring plane (55). Once enough small particles are brought into the D ring region, exospheric drag would quickly drain them into the planet, as observed by Cassini.

We conjecture that one or more transient events occurred in the recent past that disturbed the D ring, or changed its mass and particle size distributions so that tenuous gas drag can more quickly cause it to fall into the planet. The latest such event appears to have been the one that perturbed the D68 ringlet (17). However, the weak correlation shown in Fig. 5 is not compelling. Evidence of ionospheric depletion observed well before the formation of bright clumps in the D68 ringlet suggests that the material infow may have been taking place for a longer period of time (2). Therefore, we examined the evidence for D ring perturbations over a longer time scale.

The D ring structure of irregularly spaced bands or belts has changed markedly since the Voyager flyby (56). A pattern within the ring has been interpreted as a vertical spiral ripple, possibly the result of ongoing wrapping by orbital evolution of particles in the initially tilted ring. From the wavelength of the wrap, which shortens with time, the event was dated to the early 1980s (56). The ripple was later found to extend through the C ring (55), indicating that the tilt was imposed by an impacting stream of rubble, perhaps from a disrupted comet 1 to 10 km in size with an extended node crossing the D and C rings. The event may have had two parts, separated by months (57). There is also evidence in Voyager data for two other disturbances that occurred in 1979 (58). All this sporadic disruption could plausibly have altered the properties of the D ring in such a way that today's flux (and/or today's D ring) are not necessarily typical of the last 100 million years. We expect these events to have happened at the same average rate going backward, producing variability in the D ring.

Our results for the delivery of ring materials have implications for the composition of Saturn's deep atmosphere (stratosphere and troposphere). Previous modeling (7) has suggested that the delivery of oxygen, in the form of water, can explain the presence of CO seen in the stratosphere. In addition to water, we observe carbon monoxide and carbon dioxide influx that can contribute to the oxygen inventory (Fig. 6).

Because of the influx of CH\(_4\) and other sources of carbon, Saturn may have acquired an apparent methane enrichment (i.e., higher C/H ratio) relative to the protosolar value. Observations using the CIRS instrument onboard Cassini indicate that Saturn's methane enrichment over the protosolar value is 2.25 \pm 0.55 times the enrichment seen in Jupiter (59). Our INMS observations indicate an influx of methane between 3 \times 10^{20} and 2 \times 10^{29} molecules per second entering the equatorial atmosphere, and 2.5 times as much mass in the form of other organics. If we assume that inflowing methane spreads over the globe, this is equivalent to an influx of 7 \times 10^{16} or 4.8 \times 10^{16} m^2 s^{-1} throughout the atmosphere. By calculating the column density of methane in the thermosphere, stratosphere, and troposphere above an altitude of 50 km, where the contribution function of CIRS peaked (59), we can estimate how long the observed methane influx from the rings would need to be sustained to raise the enrichment to 2.25 times that of Jupiter. The estimated time is \(-7\) million to 110 million years—within approximately an order of magnitude of the estimated lifetime of the rings themselves (see above). This slow build up occurs in the stratosphere and troposphere, because the predominant methane flux at this altitude is...
from the deep interior produced by recycled heavier hydrocarbons that photochemically formed in the stratosphere and later diffused down into the interior. Thus, the methane flux from above provides a very slow shift in the steady-state concentration that builds up over time in the stratosphere and troposphere. The organic carbon nanomaterial, with a mass influx 2.5 times that of methane, could be chemically recycled deep in the atmosphere to increase the methane content in the deeper interior and drive a larger interior outflux of methane. However, our derived infalling material composition (Fig. 6) includes influx of NH₃, and it is unclear whether prolonged, continuous delivery of ring-derived NH₃ would be consistent with existing upper limits on the ¹⁵N/¹⁴N ratio in Saturn (60).

Conclusions

The Cassini INMS measured in situ the atmospheric and ionospheric composition of Saturn’s equatorial atmosphere during a series of flybys between the atmosphere and the D ring in the Grand Finale phase of the mission. Water, methane, ammonia, carbon monoxide and/or molecular nitrogen, and carbon dioxide enter Saturn’s atmosphere from the D ring along the ring plane. This influx is expected to affect the equatorial ionospheric chemistry by converting the H⁺ and H₂⁺ ions into heavier molecular ions, producing a depletion of ionospheric density previously observed in radio occultation observations (60). However, this may not explain the full extent of small-scale electron depletions observed by other Cassini instruments (33). INMS data include evidence for an influx of organic-rich nanoparticles that further modifies the composition and structure of the equatorial ionosphere and may circulate throughout the low- and mid-latitude thermosphere. Over long time scales, this infalling material may affect the carbon and oxygen content of the observed atmosphere.

Methods

The data on the D68 ringlet brightness distribution (Fig. 5) are from a sequence of images obtained by the Imaging Science Subsystem (ISS) onboard the Cassini spacecraft on day 229 of 2017, during rev 289. All images were calibrated using the standard CISSCAL routines, which remove dark currents, apply flat-field corrections, and convert the observed brightness data to I/F, a standardized measure of reflectance that is unity for a surface illuminated and viewed at normal incidence (62, 63). These calibrated images were geometrically transformed with the appropriate SPICE kernels (64), and the pointing was refined on the basis of the observed locations of stars in the field of view (27). For each image, the brightness data were then reprojected onto regular grids of radii and inertial longitude (i.e., longitude measured relative to the ascending node of the rings in the J2000 coordinate system). Each column of the reprojected maps then provides a radial profile of D68 at a single inertial longitude. Radial profiles were co-added to generate longitudinal brightness profiles. Because the ring orbit overlaps the planet, these profiles are constructed in a corotating longitude system with an assumed mean motion of 1751.7° per day and a reference epoch time of 300000000 TDB (Barycentric Dynamical Time), which is 2009-185T:18:54 UTC (Coordinated Universal Time).

The Cassini images did not have sufficient spatial resolution to discern D68’s internal structure, so the ringlet’s brightness is quantified in terms of its equivalent width (EW), which is the radially integrated I/F of the ringlet over the radius range 67,550 to 67,700 km above a background level that is fit to the signal levels on either side of the ringlet (67,000 to 67,500 km and 67,750 to 68,250 km, respectively). The estimates of the ringlet’s equivalent width are converted to normal equivalent width (NEW) by multiplying the EW values by the cosine of the ringlet’s emission angle. For features with low optical depth such as D68, NEW is independent of ring opening angle.

REFERENCES AND NOTES


Waite et al., Science 362, eaat2382 (2018) 5 October 2018

11 of 12
ACKNOWLEDGMENTS

We gratefully acknowledge the support of the Cassini project in the flawless execution of the Cassini Grand Finale phase; the late Hasso Niemann and his NASA GSFC team that built a superb instrument and the flawless operation of the IMMS team; and the Cassini INMS team was supported by NASA JPL subcontract (NAST30001T19760012), and the INMS science support grant NNX15AG63G (M.E.P.). J.-E.W., L.Z.H., and M.M. were supported by the Swedish National Space Board (SNSB) for work and data from the RPWS/UP instrument on board Cassini. Research at the University of Iowa was supported by NASA through contract 145150 with the Jet Propulsion Laboratory. J.C. was also supported by the Cassini project through his Interdisciplinary Scientist grant, NASA WBS 432162.02.01.02. D.G.M. was supported for his contribution by the NASA Office of Space Science under Task Order 033 of contract NAS5-97271 between NASA Goddard Space Flight Center and Johns Hopkins University. W.T. was supported by Taiwan Ministry of Science and Technology grant 106-2112-M-003-035. Author contributions: J.H.W., R.S.P., and M.E.P. planned the observations and discussed the interpretation of the Cassini Grand Finale phase of the mission. R.S.P. led the instrument operations uplink and downlink process; R.S.P., M.E.P., K.E.M., T.E.C., and J.H.W. contributed to the analysis of the dataset. J.H.W., R.S.P., K.E.M., T.E.C., J.B., C.R.G., and M.E.P. wrote the initial text; J.H.W., K.E.M., T.E.C., R.Y., and J.H.W. contributed to the analysis of the dataset; J.H.W., R.S.P., K.E.M., T.E.C., J.B., C.R.G., and M.E.P. provided information about the rings and their associated atmosphere; D.G.M. and M.E.P. provided insight into the compositional and structural properties of the rings from the Cassini MIMI investigation; W.S.K., J.-E.W., L.Z.H., M.M., and A.P. provided complementary information about the ionosphere as measured by the Cassini RPWS investigation; T.E.C., A.N., and L.M. provided ionospheric modeling; and J.B., S.C., B.T., and J.G. contributed to modeling and/or experiments concerning the interaction of the gas with the IMMS antechamber at high impact velocity (fragmentation, chemisorption, and mass transport processes). M.M., J.C., D.Y., C.G., S.L., W.H., and W.T. provided information about the rings and their associated atmosphere; D.G.M. and M.E.P. provided insight into the compositional and structural properties of the rings from the Cassini MIMI investigation; W.S.K., J.-E.W., L.Z.H., M.M., and A.P. provided complementary information about the ionosphere as measured by the Cassini RPWS investigation; T.E.C., A.N., and L.M. provided ionospheric modeling; and J.B., S.C., B.T., and J.G. contributed to modeling and/or experiments concerning the interaction of the gas with the IMMS antechamber at high impact velocity (fragmentation, chemisorption, and mass transport processes).

Competing interests: The authors declare no competing interests.

Data and materials availability: INMS data from the Grand Finale phase of the Cassini mission are available on NASA’s Planetary Data System at https:// pardon the previous text, it seems to be a duplicate.
Chemical interactions between Saturn’s atmosphere and its rings


Science 362 (6410), eaat2382.
DOI: 10.1126/science.aat2382

Cassini’s final phase of exploration

The Cassini spacecraft spent 13 years orbiting Saturn; as it ran low on fuel, the trajectory was changed to sample regions it had not yet visited. A series of orbits close to the rings was followed by a Grand Finale orbit, which took the spacecraft through the gap between Saturn and its rings before the spacecraft was destroyed when it entered the planet’s upper atmosphere. Six papers in this issue report results from these final phases of the Cassini mission. Dougherty et al. measured the magnetic field close to Saturn, which implies a complex multilayer dynamo process inside the planet. Roussos et al. detected an additional radiation belt trapped within the rings, sustained by the radioactive decay of free neutrons. Lamy et al. present plasma measurements taken as Cassini flew through regions emitting kilometric radiation, connected to the planet’s aurorae. Hsu et al. determined the composition of large, solid dust particles falling from the rings into the planet, whereas Mitchell et al. investigated the smaller dust nanograins and show how they interact with the planet’s upper atmosphere. Finally, Waite et al. identified molecules in the infalling material and directly measured the composition of Saturn’s atmosphere.


Use of this article is subject to the Terms of Service