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Oxygen Ions Observed Near Saturn's A Ring

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Ions were detected in the vicinity of Saturn's A ring by the Ion and Neutral Mass Spectrometer (INMS) instrument onboard the Cassini Orbiter during the spacecraft's passage over the rings. The INMS saw signatures of molecular and atomic oxygen ions and of protons, thus demonstrating the existence of an ionosphere associated with the A ring. A likely explanation for these ions is photoionization by solar ultraviolet radiation of neutral O₂ molecules associated with a tenuous ring atmosphere. INMS neutral measurements made during the ring encounter are dominated by a background signal.

A tenuous atmosphere in the vicinity of the saturnian rings was predicted to exist as a consequence of the sputtering of atoms and molecules from ring particles resulting from collisions with energetic ions, with micrometeoroids, or with solar photons (1, 2), although the energetic ion fluxes observed over the rings were very small (3). The ring particles are thought to primarily consist of water ice (4), indicating that sputtered or photoproducted material should consist of water molecules or species formed from water molecules. In particular, it has been suggested that O₂ should be the main constituent of a ring-plane atmosphere, and O₂ is known to be a product of the radiation-induced decomposition of ice (1, 5, 6). A tenuous ring ionosphere was also predicted to be present at Saturn (7).

The INMS (8) has two different inlets: the open source, which allows ions or neutral species to enter the analyzer, and the closed source, in which neutral species enter an antechamber before being ionized. For open-source-ion (osi) mode, the incident ions are deflected by quadrupole switching lenses, set to appropriate voltages, and then guided to the radio-frequency quadrupole mass analyzer, which selects the mass-to-charge ratio. The ions are then detected with a secondary electron multiplier. For the closed-source-neutral (csn) or open-source-neutral (osn) measurements, electrons generated by heating of the W filaments are used to ionize some fraction of the neutral particles, and the resulting ions are then analyzed (8, 9). The instrument is

tuned to specific incident particle speeds, and this compensation speed was set to 15 km/s for the time period of 4:00:00 to 4:06:30 coordinated universal time (UTC) on 1 July 2004 (day 183 of the year). The compensation speed just before this time period was 20 km/s and just after this time period was 5 km/s. At 4:06:30 UTC, the instrument switched from osi to osn mode. The switching lens transmission is sensitive to speeds within $\approx 10\%$ of this compensation speed (8, 9) for both open-source modes. The open-source field of view (FOV) is close to 6° (full width). The instrument detects ions that are present in a small volume in velocity space centered at the compensation velocity (10).

A mass-time plot for the INMS open-source signal (Fig. 1) shows a high count rate for mass numbers 1, 16, and 32, which can be interpreted as a result of H⁺, O⁺, and O₂⁺ ions, respectively. The count rate before 4:00 UTC was low. For O⁺ and O₂⁺ ions, the count rate was greatest between 4:00 and 4:01 UTC

and between 4:02 and 4:06 UTC. At later times, the instrument switched to neutral mode. For H⁺ ions, the count rate was highest between 4:02 and 4:06 UTC. During this time period, the spacecraft was about 7000 km above the outer part of the A ring at a radial distance of 2.2 Saturn radii (R_s). The peak O₂⁺ count rate was ≈ 200 counts per second at 4:05 UTC. During the total of ≈ 2 s of the observing period from 4:00 to 4:06:30 UTC, devoted to measuring mass-32 ions, the total number of counts was about 150 (11).

The mass spectrum (Fig. 2) created from osi observations (Fig. 1) shows noticeable peaks at masses 1, 16, and 32, confirming the presence of H⁺, O⁺, and O₂⁺, respectively. Other mass peaks with smaller signals relative to the statistical uncertainty also are evident (Fig. 2) at mass 17 (perhaps OH⁺), mass 18 (perhaps H₂O⁺), mass 23 (perhaps Na⁺), and several mass numbers near 40 to 45 (perhaps CO₂⁺ with poor velocity compensation).

The count-rate time variations (Fig. 1) could conceivably be due either to the spatial distribution of the ions (in this case, the scale size is on the order of 1000 km) or to the variations in INMS pointing, which resulted from changes in the spacecraft attitude (or a combination of these). If we assume the latter as a working hypothesis, then the INMS

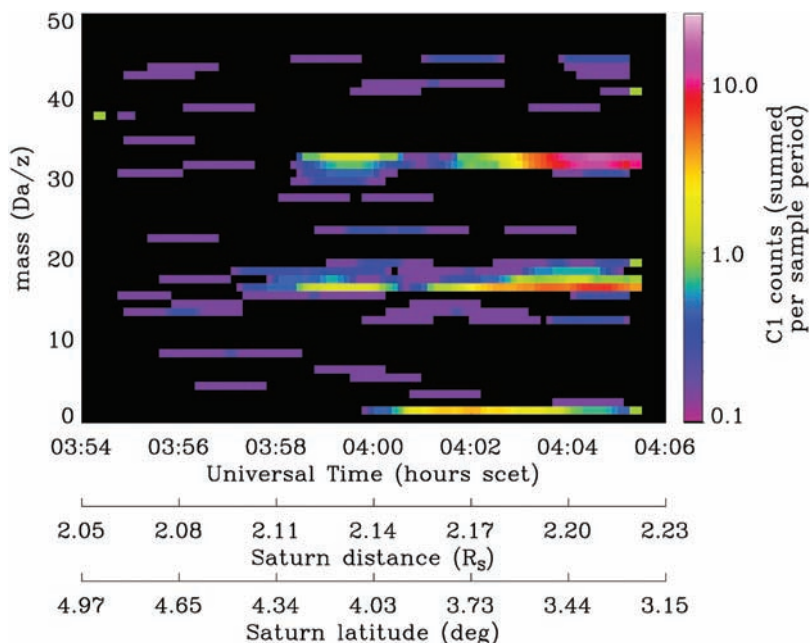


Fig. 1. Cassini INMS osi count rate (the color scale bar) versus mass number on the ordinate and Universal Time (scet) on the abscissa. Radial distance from the center of Saturn (in units of Saturn radii) is also shown. Da/Z, daltons per charge.

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measurements can provide information on the ion distribution function over the A ring. The mass 16 and 32 data points used for Figs. 1 and 2 were averaged over 30-s intervals and placed in velocity space with the use of information on the INMS compensation velocity and pointing versus time. The INMS only observed a small region of velocity space (10), but within the observed region, the highest count rates were found for low vertical velocities (i.e., with respect to the ring plane) and for horizontal velocities (i.e., parallel to the ring plane) of about 5 km/s with respect to corotation. These measurements are consistent with either shell or ring distribution functions (12), but the existence of ions with smaller velocities with respect to corotation cannot be excluded on the basis of the INMS measurements. Indeed, measurements made by the Cassini Plasma Spectrometer (CAPS) instrument over the A and B rings (13) were consistent with co-rotating oxygen ions with a 0.75-eV temperature, suggesting the existence of ions with speeds closer to corotation than a few kilometers per second.

The count rate can be used to determine the ion flux into the INMS open-source inlet (14). We found that the average fluxes for masses 1, 16, and 32 (Fig. 2) are $3900 \text{ cm}^{-2} \text{ s}^{-1}$, $900 \text{ cm}^{-2} \text{ s}^{-1}$, and $2900 \text{ cm}^{-2} \text{ s}^{-1}$, respectively. The peak count rates, and hence ion fluxes, for the time period near 4:04 UTC are about a factor of 2 higher than these average values (Fig. 1). The ion densities detected by the INMS near the compensation speed (15) can be found by dividing the fluxes by the compensation speed and are 0.0047 cm^{-3} (H^+), 0.0013 cm^{-3} (O^+), and 0.004 cm^{-3} (O_2^+). The peak densities are about twice these values and can also be used to determine peak ion distribution function values (16). The ratio of O^+ to O_2^+ is about 0.3, and the ratio of H^+ to O_2^+ is about 1.

Estimating absolute and total ion densities from the INMS data is difficult, because the INMS only sees a small fraction of the total ion velocity distribution. For a ring distribution function (12), the INMS would detect about 10% of the total distribution, whereas for a filled-in spherical distribution, INMS would

detect about 1% of the total. Our estimated total ion number densities for these two assumptions are 0.1 and 1 cm^{-3} , respectively, for both H^+ and O_2^+ and 0.03 and 0.3 cm^{-3} , respectively, for O^+ . The total electron density is then about $N_e \approx 0.2$ to 2 cm^{-3} . However, if a much colder component is also present, as suggested by CAPS (13), then the INMS might have observed an even smaller fraction of the total ion distribution than 1%, suggesting total densities greater than the above values. The electron density measured by the Cassini Radio and Plasma Wave Science (RPWS) experiment (17) increased from 6 to 25 cm^{-3} during the INMS observation period.

The INMS also operated in its csn mode during 3:54:41 and 4:06:26 UTC. The INMS is much less sensitive to neutral species because of the small fraction that are ionized in the instrument. A further complication was that the instrument cover had just been jettisoned about an hour earlier and some of the gas trapped in the instrument throughout the 7-year-long cruise phase of the mission was still present, resulting in a background count rate for all observable mass channels (18).

Photoionization of ring atmosphere neutrals by solar extreme ultraviolet or soft x-ray radiation seems the most likely explanation for the A-ring ions measured by the INMS, because the fluxes of energetic particles are negligible, probably because of absorption of the energetic plasma by the rings (3, 13). The spacecraft was in Saturn's shadow at the time of the INMS observations; however, the outer A ring had been exposed to sunlight only an hour or so previously, which is considerably less than the ion lifetime (probably several hours, on the order of the ion bounce and mirror time). Cassini flew on the shady side of the rings; however, the optical depth of the A ring is ≈ 0.5 and considerable solar radiation can make it through the ring (4). Adopting a box model of the atmosphere-ionosphere environment over the ring in which ion production resulting from photoionization is balanced by transport loss of ions to the ring (after magnetic mirroring), we found the following approximate equation relating the ion density to the molecular oxygen density:

$$N(\text{O}_2^+)/N(\text{O}_2) \approx T_{\text{bounce}} I \approx 10^{-5} \quad (1)$$

where I is the ionization frequency for O_2 (19, 20) and T_{bounce} is the ion lifetime (21). Similar relations for the H^+ and O^+ densities and the electron density can also be derived. The main source of O^+ ions is probably dissociative photoionization of O_2 , although ionization of O could also make a contribution (20). Given our earlier estimate of the O_2^+ density $N(\text{O}_2^+) \approx 0.1$ to 1 cm^{-3} , Eq. 1 suggests that the neutral O_2 density is about 10^4 to 10^5 cm^{-3} , consistent with Ip's 3000 cm^{-3} O_2 density prediction (1). These densities are near the threshold of detection of the neutral mass

spectrometer. The high values of the electron density measured by RPWS (17) imply either a neutral oxygen density substantially exceeding 10^5 cm^{-3} or an ion lifetime significantly greater than the bounce time.

The INMS, CAPS (13), and RPWS (17) instruments have revealed the existence of an atmosphere and an ionosphere/plasma in the vicinity of Saturn's A ring. The icy rings of Saturn generate a molecular oxygen-dominated atmosphere rather than one containing other water products (e.g., OH , OH^+ , H_2O^+ , and H_3O^+), which have shorter lifetimes as a result of sticking on the ring particle surfaces.

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10. The INMS in osi mode can measure ions in a velocity space volume approximately equal to the area of the FOV (at the compensation speed) multiplied by the length of compensation region ($\pm 1.5 \text{ km/s}$). The compensation speed was set to 15 km/s for 4:00 to 4:06:30 UTC and the volume was $\Delta V \approx 10^{16} (\text{cm}^3)$.
11. The instrument electronics operation is such that for mass numbers greater than about 32 and for higher speeds, the velocity compensation cannot be perfectly achieved and there is a "spreading" of the signal to adjacent mass numbers. In particular, O_2^+ is seen at mass 31 as well as at 32. This is not a problem for lower mass numbers or for lower speeds, such as the 6-km/s ram speed (i.e., head-on gas speed) that the INMS will experience at Titan.
12. Ions created in the ring-plane environment from the ionization of neutral species moving at the local keplerian speed ($\approx 15 \text{ km/s}$ at the outer A ring) respond to the saturnian magnetic and corotation electric fields by both gyrating about the magnetic field and moving around the planet at the corotation speed ($\approx 21 \text{ km/s}$ at the outer A ring). In addition to this motion in the ring plane (which can be called horizontal), the ions should also have a small ($\approx 1 \text{ km/s}$) velocity component along the magnetic field (approximately perpendicular to the ring plane, or vertical), which they inherit from the motion of the parent neutral atoms and molecules acquired during the surface ejection process and/or during gas interactions with the grains (1, 5, 6). The statistical distribution of these ions form a circle, or ring, in velocity space. This type of pick-up ion distribution is well known in other space environments (22, 23). Near the outer A ring, the gyration speed of a newly formed ion in the co-rotating frame of reference is 5 to 6 km/s (i.e., the ring radius). The ring distribution can evolve into other distributions (such as a shell distribution) resulting from collisions or wave-particle interactions associated with magnetic fluctuations or waves (22).
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14. The INMS osi count rate, C , is given in terms of the flux of ions into the instrument and the incident ion energy by the relation: C (counts per second) = $3.95 \times 10^{-3} + 5.35 \times 10^{-4} E$ (eV) (molecules $\text{cm}^{-2} \text{ s}^{-1}$). The energy of an ion with a mass number of A (atomic mass units) is E (eV) = $0.0052Av^2$, where v is measured in kilometers per second. For $A = 1, 16$, and 32 and $v = 15 \text{ km/s}$ (the INMS compensation speed on this occasion), $E = 1.2 \text{ eV}$, 19 eV , and 37 eV , respectively. We then found count rates per ion unit

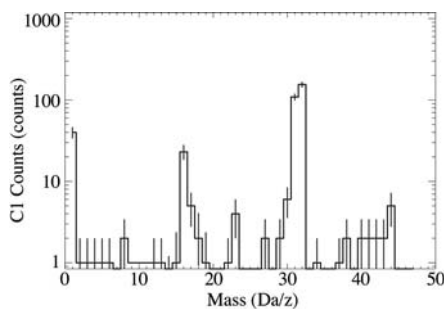


Fig. 2. INMS osi mode mass spectrum showing the number of counts versus mass number for times between 3:54:41 and 4:06:26 UTC. The 1σ statistical error is shown.

flux for $A = 1, 16,$ and 32 of $0.0046, 0.010,$ and $0.0240,$ respectively.

15. During its normal open-source (ions or neutrals) operation in the ionosphere and atmosphere of Titan, where the molecules are cold and the relative velocity is dominated by the spacecraft ram velocity, the entire distribution is within the instrument's compensation region volume (10), defined by the energy/velocity acceptance along the FOV and the velocity width perpendicular to this associated with the angular width of the FOV. However, during operations in the period after orbit insertion (over the A ring), only a small fraction of the ion distribution is captured in the compensation region.
16. The peak value of the distribution function, f , from INMS measurements for time periods when the compensation velocity is near the ring is the INMS density divided by the velocity space compensation volume (10). For $H^+, O^+,$ and O_2^+ , the peak f values

are about $10^{-18} \text{ s}^3/\text{cm}^6, 3 \times 10^{-19} \text{ s}^3/\text{cm}^6,$ and $10^{-18} \text{ s}^3/\text{cm}^6,$ respectively.

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18. The background rate of INMS in the csn mode has steadily diminished in the months after Saturn Orbit Insertion.
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21. Ions moving away from the ring plane along the magnetic field are reflected by the magnetic mirror formed by converging field lines and will return to the ring plane where they are removed from the plasma environment/ionosphere. This bounce time, T_{bounce} is ≈ 3 hours and should also be the ion lifetime. However, because of a small northward offset of Saturn's magnetic dipole (24), some ions with very small vertical velocities might be trapped and have longer lifetimes.
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25. We thank R. Johnson and F. Crary for useful and insightful discussions and comments. We are also very grateful for the hard work and dedication of our engineering, technical, and operational staff: G. Fletcher, E. Walter, R. Miller, J. Xu, J. Parajeko, D. Gell, and R. Thorpe. We thank D. Eddy, I. Robertson, and T. Hunt-Ward for technical help with the figures and text. Financial support from the NASA Cassini project is acknowledged.

28 September 2004; accepted 2 December 2004
10.1126/science.1105734

REPORT

Composition and Dynamics of Plasma in Saturn's Magnetosphere

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During Cassini's initial orbit, we observed a dynamic magnetosphere composed primarily of a complex mixture of water-derived atomic and molecular ions. We have identified four distinct regions characterized by differences in both bulk plasma properties and ion composition. Protons are the dominant species outside about $9 R_S$ (where R_S is the radial distance from the center of Saturn), whereas inside, the plasma consists primarily of a corotating comet-like mix of water-derived ions with $\sim 3\%$ N^+ . Over the A and B rings, we found an ionosphere in which O_2^+ and O^+ are dominant, which suggests the possible existence of a layer of O_2 gas similar to the atmospheres of Europa and Ganymede.

Most of what was known about Saturn's magnetosphere before Cassini's arrival was derived from the Pioneer 11 and Voyager 1 and 2 encounters from 1979 to 1981 (1–5) and from models based on that data (6–8). The measurements reported here were made with the Cassini plasma spectrometer (CAPS) (9–11) during the initial passage of the Cassini spacecraft through the near-equatorial regions of Saturn's magnetosphere. The CAPS instrument is made up of three plasma sensors. The first is the ion mass spectrometer (IMS), which measures ion energy per charge (E/Q) between 1 V and 50 kV with a resolution of $\Delta E/E = 0.17$. It simultaneously measures ion mass per charge (M/Q) from 1 to ~ 100 atomic mass units (amu) per charge, e , with a mass resolution $M/\Delta M \approx 60$. The second sensor is the electron spectrometer (ELS), which measures electron energy from 0.6 eV to 28 keV with $\Delta E/E = 0.17$. The IMS and ELS are able to detect ion and electron densities as low as $\sim 10^3 \text{ m}^{-3}$. The third sensor is the ion beam spectrometer (IBS), which measures ion E/Q with a very

high resolution of $\Delta E/E = 0.017$, which is appropriate for narrowly beamed distributions.

The energy-time spectrogram (Fig. 1) and bulk plasma parameters (Fig. 2) give a broad overview of structures and events found 24 hours on either side of Cassini's closest approach to Saturn [02:39 universal time (UT) on 1 July 2004]. Within this time period on both inbound and outbound trajectories, we observed four regions with different physical and chemical characteristics: (i) The outer, or high-latitude, magnetosphere contains tenuous hot plasma dominated by H^+ . (ii) A region we term the outer plasmasphere consists of highly variable, partially corotating plasma that contains a mixture of $H^+, O^+,$ and water-group ions (denoted as W^+ and defined as a combination of $OH^+, H_2O^+,$ and H_3O^+). (iii) The inner plasmasphere is less variable and closer to rigid corotation than the outer plasmasphere, and is made up primarily of O^+ and W^+ . (iv) A layer of plasma consisting of O^+ and O_2^+ is located directly over the A and B rings. The boundaries separating these four regions are

distinguished by changes not only in bulk plasma properties but also in chemical composition.

On the spacecraft's inbound trajectory, Saturn's magnetopause crossed over the spacecraft nine times between 34.6 and $30.6 R_S$ ($1 R_S = 60,330 \text{ km}$). Just inside the magnetopause, plasma densities fell below the detection limits of the IMS. In particular, N^+ , which might have been expected in the region of Titan's orbit ($20.25 R_S$), was not detected on either the inbound or outbound legs, possibly because the spacecraft was

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