Cassini Finds an Oxygen–Carbon Dioxide Atmosphere at Saturn’s Icy Moon Rhea

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The flyby measurements of the Cassini spacecraft at Saturn’s moon Rhea reveal a tenuous oxygen (O₂)–carbon dioxide (CO₂) atmosphere. The atmosphere appears to be sustained by chemical decomposition of the surface water ice under irradiation from Saturn’s magnetospheric plasma. This in situ detection of an oxidizing atmosphere is consistent with remote observations of other icy bodies, such as Jupiter’s moons Europa and Ganymede, and suggestive of a reservoir of radiolytic O₂ locked within Rhea’s ice. The presence of CO₂ suggests radiolysis reactions between surface oxidants and sputtered or outgassing of CO₂ endogenic to Rhea’s ice. Observations of outflowing positive and negative ions give evidence for pickup ionization as a major atmospheric loss mechanism.

On 2 March 2010, the Cassini spacecraft executed a flyby of Saturn’s icy moon Rhea, with a trajectory inbound toward Saturn passing 97 km over the surface at 81° north latitude. The Ion Neutral Mass Spectrometer (INMS)—a quadrupole mass analyzer equipped with an anechamber and electron-impact ionizer for in situ collection and detection of neutral gas (I)—was operated during the flyby with the anechamber inlet pointed favorably at an angle of 44° to Cassini’s trajectory, enabling the measurement of neutral species. INMS detected a tenuous atmosphere of oxygen and carbon dioxide in mass channels 32 and 44 daltons, reaching peak densities along the trajectory of 5 and 2 ± 1 × 10¹⁰ molecules per m³, respectively. A highly non-uniform atmosphere was observed, with the CO₂ seen almost exclusively on the outbound portion of the trajectory over the day-lit hemisphere (Fig. 1). In contrast, the O₂ profile is more symmetrical about the point of closest approach, but it is nevertheless shifted slightly outbound to the day side (Fig. 1).

Spectra from the Cassini Plasma Spectrometer (CAPS) (2), acquired during the more distant 502- and 5736-km flybys on 26 November 2005 and 30 August 2007, also show clear signatures (Fig. 2) symptomatic (3) of outflowing streams of positive and negative ions, which are produced by ionization of the atmosphere and electron capture, respectively. These ions are subsequently swept up into Saturn’s rotating magnetosphere (4). The timing of the positive and negative ion signatures inbound and outbound from Rhea (Fig. 2) is consistent with the expected E × B cyclotidal trajectories (where E and B are the electric and magnetic fields, respectively) of pickup ions in the mass ranges to 26 and 56 daltons (possibly O₂⁺ or CO₂⁺) and to 26 daltons, respectively; thus, we tentatively identify the negative species as O⁻. The mass uncertainty from the CAPS energy and angular resolution (2), as well as the still-uncertain corotation electric field and corotation speed in Rhea’s plasma wake (5). Unlike the 2005 encounter, only positive ions were detected during the 11 times more distant 2007 flyby, suggesting rapid (6) removal of loosely bound electrons from the negative ions by photo or electron impact ionization as the ions move away from Rhea.

The in situ detection of O₂ and CO₂ at Rhea is consistent with remote observations of Jupiter’s icy moons, where the Galileo spacecraft’s Near-Infrared Mapping Spectrometer observed resonantly scattered 4.26-μm infrared emission from atmospheric CO₂ at Callisto (7), and the Hubble Space Telescope measured 1304 and 1356 Å ultraviolet fluorescence from electron-impact dissociatively excited atmospheric O₂ at Europa and Ganymede (8). Oxygen at Europa and Ganymede is generated by radiation chemistry and sputtered from the surface into the atmosphere by bombarding ions and electrons from Jupiter’s magnetosphere (8). The Jupiter findings, and the detection by Cassini of O₂ at ultraviolet (UV) photodecomposition of ice in Saturn’s rings (9), have long suggested the possibility of oxygen atmospheres around the saturnian icy satellites (10), which orbit inside Saturn’s magnetosphere. Ganymede’s ice (11) and that of Europa and Callisto (12) also exhibit the weak 5770 and 6275 Å optical absorption signatures of trapped radiolytic O₂ (13), which has been shown in laboratory experiments to lead to ozone as a byproduct (14), along with eventual O₂ ejection from the surface through sputtering (15). Rhea and Saturn’s icy moon Dione are especially interesting because O₃ is present in their surface ices (16), a trait that they share with Ganymede (17). Together with the existence of ozone in Rhea’s ice, the detection of an O₂ atmosphere is consistent with surface radioactivity, as seen at other icy satellites, and indicative of O₂ trapped in the surface ice.

On the basis of CAPS and Magnetospheric Imaging Instrument (MIMI) measurements of the saturnian ion and electron plasma, as well as updated laboratory estimates of O₂ production and desorption from ice irradiated with different projectiles and energies, we have modeled the expected production of O₂ from different radiation sources (18). The principal oxygen source in the model is bombardment by water group ions (W⁻) from Saturn’s corotating plasma (Table 1), which sweep past Rhea along its orbit while preferentially bombarding its trailing hemisphere. The oxygen is, therefore, produced preferentially on the
Fig. 1. (A) INMS 32-dalton measurement (32) of the O₂ density along Cassini’s trajectory versus time during the 2 March 2010 Rhea encounter. The black vertical dotted line indicates that the closest approach (CA) was 17:40:39 UT at 96.8-km altitude and nearly simultaneous (later by ~0.05 s) with solar terminator traversal to Rhea’s day side. The blue dashed curve denotes along-track density predicted by a Monte Carlo simulation of the O₂ atmosphere that assumes 100/40 K day/night surface temperatures, respectively (25). (B) Same as (A) for CO₂ in the 44-dalton mass channel. (C) Diagrammatic equatorial view of Rhea looking perpendicular to the Cassini 2010 trajectory (red line in Rhea’s reference frame) on the same time scale as in (A) and (B). The vantage point at 81.8° longitude and 8.9° north latitude is near the apex (90° longitude) of Rhea’s leading hemisphere. Cassini’s motion toward Saturn at 8.6 km/s was nearly perpendicular (at 88.8°) to the day-night terminator (shown at the time of CA), with CA at 81.1° north latitude, 263.4° longitude. Rhea’s orbit and Saturn’s corotation direction point out of the page and perpendicular to the magnetic and corotation electric fields $\mathbf{B}$ and $\mathbf{E}$. Also shown is the O₂ density cross section predicted by the Monte Carlo model.

Fig. 2. (A) Diagrammatic Rhea north polar view with the 26 November 2005 Cassini flyby trajectory (black line in Rhea’s reference frame) during which CAPS detected pickup ions. The time scale is matched to that of (B) and (C). The day and night hemispheres are shown during CA at 22:37:39 UT. The trajectory traversed Rhea’s plasma wake, with CA at 502-km altitude, 226 km south (Fig. 1) of the equator. Our model prediction of the O₂ density (226-km south cross section) is also shown. The O₂⁺ and O⁺ (orange) and CO₂⁺ trajectories (blue) are those required to enter anodes 4 and 3 (33) of the CAPS Electron Spectrometer (ELS) and Ion Mass Spectrometer (IMS) at the time and energy of the ion signatures. The trajectories assume (in Saturn’s reference frame) a $\mathbf{B}$ of 26 nT (34) and a corotation electric field $\mathbf{E}$ [within uncertainty (31) of 1.77 (O₂⁺), 0.35 min] or 1.51 (CO₂⁺) V/km. Before ionization, most atmospheric neutrals have thermal speeds less than 1 km/s, so $\mathbf{E}$ is optimized such that ions backtracked from Cassini come nearly to rest (the trajectory starting point). FOV, field of view. (B) ELS negative particle flux spectrogram from anode 4 (20° FOV), which had optimal pointing. Negative pickup ions are indicated by the sharp feature near 22:41 UT (±0.35 min) and 1.14 (±0.15) keV over the electron background. (C) Positive ions from IMS anode 3: Pickup ions produce the sharp 22:32 UT (±0.5 min), 2.06 (±0.2)–keV signature over the background of (mostly) corotating H⁺/W⁺ (32).

trailing hemisphere. Relative to the amount of energy deposited by the different radiation sources, the W⁺ ions are also the most efficient O₂ producers (Table 1). Because of their mass, these ions are the most effectively stopped on impact within the ice; that is, they deposit the most energy close to the material surface where, according to experiments, O₂ synthesis is favored most (18). The predicted total global production rate of ~2.2 × 10²⁴ O₂ molecules per second is within the ~0.4 to 4 × 10²⁴ s⁻¹ range implied by the elevated O₂⁺ densities seen by CAPS near Rhea’s orbit (19).

In contrast to O₂, knowledge of Rhea’s CO₂ source is much less well constrained. Atmospheric CO₂ might result from sputtering of primordial CO₂ in Rhea’s ice or from radiolysis reactions between surface water molecules, radiolytic oxygen, and carbonaceous minerals or organics possibly present in the surface ice (13, 20, 21) and/or deposited by micrometeorite bombardment (22). The trailing hemispheres of Rhea and Dione both show a darkening in their visible-infrared reflectance spectrum, which is indicative of such non-ice material. At Dione, the Cassini Visible and Infrared Mapping Spectrometer (VIMS) detected the 4.26-μm absorption of CO₂ in the dark regions (22). However, the Rhea measurements are inconclusive: A possible detection of the CO₂ absorption in Rhea’s global spectrum (22) was not confirmed in subsequent VIMS mapping measurements (23) of the surface. A completely endogenic CO₂ source is also possible: for instance, outgassing of primordial CO₂ or of CO₂ produced by aqueous chemistry from Rhea’s interior, similar to scenarios suggested at Enceladus (24) and Callisto (7).
The surface source processes compete with atmospheric loss mechanisms to determine the atmospheric O2 and CO2 abundances. The loss mechanisms are Jeans escape and atmosphere-plasma interactions—that is, ionization, dissociation, charge exchange, and electron capture. The plasma-interaction channels result in fast neutral and ionized species that, depending on their point of origin (Fig. 2), either (i) collide with Rhea’s surface (and implant into the ice or adsorb or react on the surface) or (ii) escape into space directly or (for ions) by E × B pickup, as seen by CAPS.

We used a Monte Carlo approach to model the atmosphere by initializing O2 molecules according to the loss rate from plasma interactions normally equilibrated molecules with the surface on random ballistic trajectories between surface impacts. The laboratory column densities correspond to ~0.4 to 4×10^16 metric tons of trapped O2 globally on Rhea, but these are a lower limit because diffusion and micrometeorite gardening can disperse O2 into the subsurface ice.

### References and Notes

4. CAPS did not detect pickup ions during the 2010 flyby because Cassini’s path north of Rhea did not intersect the allowable ion trajectories (Figs. 1 and 2).
5. Field strengths of 1.77 and 1.51 V/m, consistent with O^+ and CO^+ (Fig. 2), yield bulk plasma speeds 61/68 (electrons) × 1014 eV/m²/s and 3.0 × 1011 O^+/m²/s, respectively, both of which are compatible with published estimates (62) and supplemental reference (44). A 49-kms bulk plasma speed with respect to Rhea (18, 22) pickup ions reaching Cassini’s 2007 position are approximately 2 min old, compared with ages of 10 (±5) s in 2005.
6. Assuming a 49-kms bulk plasma speed with respect to Rhea (18, 22), pickup ions reaching Cassini’s 2007 position are approximately 2 min old, compared with ages of 10 (±5) s in 2005.

### Table 1. Estimated O2 production from different radiation sources.

<table>
<thead>
<tr>
<th>Radiation source</th>
<th>Energy deposition (x 10^16 eV/s)</th>
<th>Estimated O2 production (x 10^12 O2/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W^+</td>
<td>14.8</td>
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</tr>
<tr>
<td>H^+</td>
<td>9.5</td>
<td>7.4</td>
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<tr>
<td>Electrons</td>
<td>73</td>
<td>38</td>
</tr>
<tr>
<td>Solar UV</td>
<td>8.1</td>
<td>4.2</td>
</tr>
<tr>
<td>Total</td>
<td>105</td>
<td>220</td>
</tr>
</tbody>
</table>

### Supporting Online Material

- www.sciencemag.org/cgi/content/full/science.1193636/DC1
- Materials and Methods
- SOM Text
- Figs. S1 to S10
- References and Notes
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- 7.5R, where R is the radius of Saturn, is photoionization by ring-atmosphere O^+ and statistically greater than R = 10.8R corresponds to 7.5R, 1.19% at 10.5R, (245). Rhea orbits at 8.7R.


- Considering the nighttime hemisphere orientation at the times of the 2 March 2010 and 26 November 2005 flybys, we reconstructed a temperature map based on Cassini Composite Infrared Spectrometer (CIRS) measurements (Fig. S16) showing 100/40 K maximum nighttime temperatures, respectively. Because the CIRS coverage did not include the poles, we assume a constant 35/75 K (26 Nov 2005, Saturn winter) and 35/55 K (2 March 2010, near Saturn equinox) beyond 75° north/south latitude.