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 organics or sputtering and/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 antechamber and electron-impact ionizer for in situ collection and detection of neutral gas (I)—was operated during the flyby with the antechamber 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 $2 \times 10^{10}$ molecules per m$^3$, 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 $E \times B$ cycloidal trajectories (where $E$ and $B$ are the electric and magnetic fields, respectively) of pickup ions in the mass ranges of 26 to 56 daltons (possibly O2$^+$ or CO2$^+$) and 13 to 26 daltons, respectively; thus, we tentatively identify the negative species as O$. The mass uncertainty results from the CAPS energy and angular resolution, 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 ice into the atmosphere by bombarding ions and electrons from Jupiter’s magnetosphere (9). The Jupiter findings, and the detection by Cassini of O2 from 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 O3 atmosphere is consistent with surface radiolysis, 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 B and 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 B of 26 nT (34) and a corotation electric field E (within uncertainty (35)) of 1.77 (O2+, O) or 1.51 (CO2+) V/km. Before ionization, most atmospheric neutrals have thermal speeds less than 1 km/s, so |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).
The surface source processes compete with atmospheric loss mechanisms to determine the atmospheric O$_2$ and CO$_2$ 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 $E \times B$ pickup, as seen by CAPS.

We used a Monte Carlo approach to model the atmosphere by initializing O$_2$ molecules according to the expected surface position-dependent production ($f_\lambda$) while allowing the molecules to execute random ballistic trajectories between surface impacts. The simulation assumed no surface adsorption, thermally equilibrated molecules with the surface on impact by reinitializing the speed with a Maxwell-Boltzmann distribution at the local surface temperature ($T_s$), and destroyed the molecules in mid-flight, according to the loss rate from plasma interactions or on leaving the Hill sphere (Jeans escape).

Our model predicts a day-side bulge due to the higher ($f_\lambda$) temperatures (and, therefore, increased scale height) that is well matched by the outbound O$_2$ tail seen by INMS (Fig. 1); i.e., the warmer day-side temperatures expand the atmospheric gas to the altitude of Cassini’s trajectory in this hemisphere. The bulge is also consistent with the predicted origin of the positive pickup ions at high altitudes during the 2005 flyby (Fig. 2).

Non-negligible night-side O$_2$ adsorption could account (26) for the model’s slight overestimate of the INMS inbound measurements (Fig. 1). The mean free path is ~6 to 30 $\times$ 10$^3$ km at the predicted day-night surface densities of ~9 to 40 $\times$ 10$^{10}$ O$_2$ m$^{-3}$ (26); therefore, the atmosphere can be considered as collisionless. The estimated Jeans escape of 6($\pm$1) $\times$ 10$^{22}$ O$_2$ s$^{-1}$ is -2.7% of the estimated total O$_2$ produced ($\sim 2.2 \times 10^{24}$ O$_2$ s$^{-1}$), with the remainder lost because of plasma interactions and pickup. The total atmospheric O$_2$ abundance is estimated to be 2.5($\pm$0.5) $\times$ 10$^{29}$ molecules, corresponding to an average atmospheric molecule lifetime of $\sim 10^4$ seconds, or ~1 day.

Whereas for O$_2$ the sticking times are short, CO$_2$ is much less volatile (27); thus, the night side could act as a much more effective cold trap for CO$_2$ condensation, possibly explaining the almost non-existent CO$_2$ signal on the night side.

<table>
<thead>
<tr>
<th>Radiation source</th>
<th>Energy deposition ($x 10^{18}$ eV/s)</th>
<th>Estimated O$_2$ production ($x 10^{22}$ O$_2$/s)</th>
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<tbody>
<tr>
<td>W$^+$</td>
<td>14.8</td>
<td>170</td>
</tr>
<tr>
<td>H$^+$</td>
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<td>38</td>
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<td>4.2</td>
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<tr>
<td>Total</td>
<td>105</td>
<td>220</td>
</tr>
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</table>

Table 1. Estimated O$_2$ production from different radiation sources.

Locally condensed CO$_2$ would be released by solar heating as the dawn terminator advances across the surface, although some CO$_2$ might be trapped for longer periods in shadowed polar regions (analogous to lunar (28) volatiles). Although surface CO$_2$ on the night side would be undetectable by Cassini VIMS (which measures reflected sunlight), CO$_2$ near the faintly illuminated poles or dawn terminator might be observable.

The estimated mean atmospheric O$_2$ column density of $3.4(\pm 0.7) \times 10^{16}$ m$^{-2}$ over Rhea’s surface is two orders of magnitude below the 2.4 to 14 and $1 \times 10^{18}$ m$^{-2}$ abundances at Europa and Ganymede (8), respectively, a difference likely attributable to the greater O$_2$ desorption flux from the warmer and more intensely irradiated Galilean satellites (29). Rhea’s atmospheric abundance is also well below the $10^{18}$ m$^{-2}$ detection limit of MIMI and the Cassini Ultraviolet Imaging Spectrograph, explaining why earlier attempts by these instruments to detect an atmosphere remotely were unsuccessful (30). In comparison, laboratory measurements on irradiated ice imply that $10^{18} \rightarrow 10^{20}$ O$_2$ m$^{-2}$ ($14, 15$) are synthesized by penetrating ions as trapped molecules inside the bulk H$_2$O$_2$ solid, from which diffusive loss is expected to be slow; thus, it is likely that a large fraction of Rhea’s oxygen is actually locked inside the moon’s ice. The laboratory column densities correspond to ~0.4 to $4 \times 10^4$ metric tons of trapped O$_2$ globally on Rhea, but these are a lower limit because diffusion and micrometeorite gardening can disperse O$_2$ 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/km, consistent with 1.7 V/km at Ganymede (37).
6. The O$_2$ and CO$_2$ sublimation energies are 0.095 eV (H$,^1$) and 0.13 eV (W$^+$, S$^+$) and 0.11 eV (H$,^2$), respectively, and mean O$_2$ temperatures ($T_s$) were 100$\times 10^4$ K at 35 K, as well as 254$\times 10^4$ K at 100 K.

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