Formation, Distribution and Loss of Rhea's O_2-CO_2 Exosphere.

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Introduction: The Cassini spacecraft's Ion Neutral Mass Spectrometer (INMS) detected an oxygen and carbon dioxide exosphere [1] during the March 2, 2010 close flyby of Saturn's icy moon Rhea (Fig. 1). Oxygen appears to form by chemical decomposition of the surface ice under irradiation by energetic particles trapped in Saturn's rotating magnetic field, while carbon dioxide may be synthesized from irradiation-driven surface reactions between oxygen and endogenic and/or exogenous organics in the surface ice, and/or escape of primordial CO_2 from the ice. The findings at Rhea compliment previous remote observation by the Hubble Space Telescope (HST) of gaseous O_2 at Ganymede and Europa [2], the Galileo spacecraft's remote observation of gaseous CO_2 at the Callisto [3], HST's detection of trapped ozone inside the surface ices of Rhea, Dione and Ganymede [4,5], and telescopic observations of surficially trapped O_2 at Ganymede [6], Europa and Callisto [7]. Thus, the presence at Rhea of atmospheric and surface oxidants as seen at Dione and the Galilean moons may suggest similar processes taking place on irradiated icy bodies throughout the universe, i.e., surface decomposition as a major source of molecules such as O_2 and possibly CO_2, and as an important driver of active and possibly complex oxidant driven chemistry on their surfaces.

Exospheric Distribution: Cassini's 2010 flyby trajectory at 8.6 km/s with respect to Rhea was nearly perpendicular (at 89°) to the day-night terminator, with closest approach taking place at 81° north latitude and 97 km. During the flyby the INMS – equipped with and antechamber and quadrupole mass analyzer to capture and analyze neutral gas - detected peak O_2 and CO_2 densities of 5 and 2 (±1) × 10^{10} molecules per m^3 occurring after closest approach, respectively, over Rhea's dayside hemisphere. The asymmetrical atmospheric distribution is consistent with our Monte-Carlo modeling, which predicts an expansion of the exospheric O_2 to the altitude of Cassini's trajectory over the warmer Rhea dayside hemisphere (Figs. 1 and 2). The model initialized molecules according to the expected position-dependent distribution of radiolysis (concentrated on the trailing hemisphere [1]), assumed random ballistic trajectories between surface impacts, thermally equilibrated re-impacting molecules with the surface by reinitializing the speed with a Maxwell-Boltzmann distribution at the local surface temperature [8], and destroyed the molecules in mid-flight according to the loss rate from pickup ionization (a fitting parameter of the simulation) or on leaving the Hill sphere. The model assumed no surface O_2 adsorption since the surface-sticking times are expected to be short in Rhea's temperature range (40-100 K [8]). By contrast, carbon dioxide is less volatile than molecular oxygen, and is therefore expected to condense onto the cold night-side until being re-released as the advancing dawn terminator re-heats the surface every 4.5 (earth) days, probably accounting for INMS's non-detection of CO_2 over the night-side (Fig. 1). Some CO_2 might also accumulate for longer periods on shadowed polar surfaces, analogous to lunar volatiles [9].

Ionization and Loss: The detection of positive and negative ions emanating from Rhea's atmosphere by the Cassini Plasma Spectrometer (CAPS) during the 26 November, 2005 and 30 August, 2007 flybys [1] indicates that the atmosphere is ionized and consequently stripped away by the ambient electric field. The energy and timing of the positive ions is consistent with CO_2^+ and/or O_2^+, and that of the negative ions corresponds to O^- (Fig. 2). While the formation of positive ions is expected and explained by photo and electron-impact ionization and charge exchange, the detection of an O^- source of similar magnitude (of the order 10^{10} ions/m^2/str/s positive and negative seen by CAPS [1]) is surprising since candidate formation processes such as dissociative electron attachment have comparatively low cross-sections [10]. The apparent important role of negative ionization as an atmospheric loss mechanism is an unexpected result which not only necessitates further study of Rhea's atmospheric physics, but places new constraints on icy satellite exospheric models generally.

Figure Captions: **Fig 1**: INMS measurement of O_2 and CO_2 in mass channels 32 and 44 amu during the 2010 Rhea flyby. Dashed line corresponds to the closest approach point, which was coincident with the day-night terminator. **Fig 2**: Schematic showing Cassini's 2010 trajectory and a simulation of the O_2 atmospheric distribution. **Fig 3**: CAPS electron spectrometer and ion mass spectrometer data from the 2005 flyby showing negative and positive pickup ions. **Fig 4**: Schematic showing Cassini's 2005 trajectory, the simulated O_2 atmospheric distribution, simulated positive (CO_2^+ & O_2^+) and negative (O^-) ion trajectories, and the position of the measured ion signatures along the trajectory.

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Figure 1

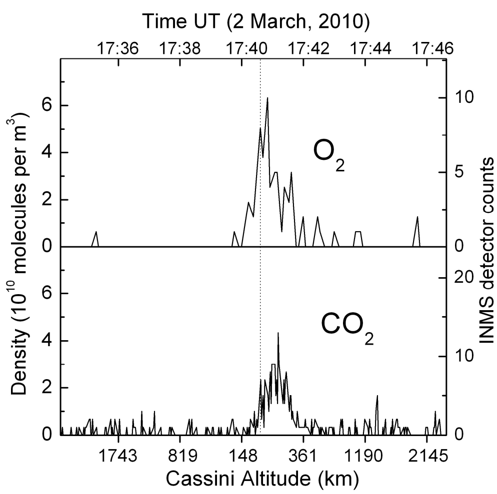

Figure 2

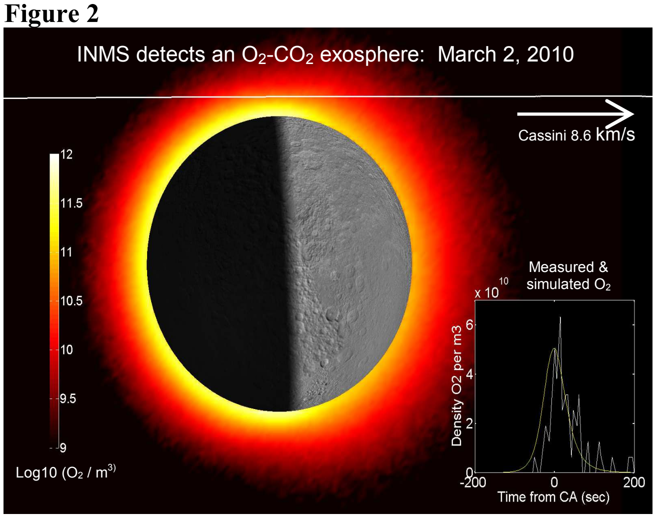

Figure 3

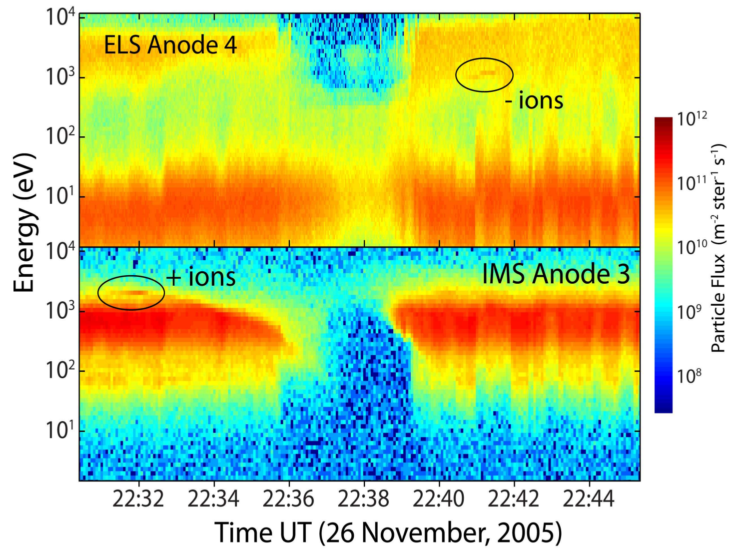

Figure 4