Cassini measurements show seasonal O_2 – CO_2 exospheres and possible seasonal CO_2 frosts at Rhea and Dione. B. D. Teolis[1], J. H. Waite[1]

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Introduction: We will present the discovery of a oxygen - carbon dioxide exosphere at Dione by the Cassini Ion Neutral Mass Spectrometer (INMS) from the 99 km December 12, 2011 equatorial Dione encounter. As shown in Fig. 1 the INMS; a quadrupole mass spectrometer equipped with an antechamber and electron impact ionizer for in situ collection and mass analysis of neutral gas, detected roughly equal O_2 and CO_2 densities of $\sim 2\times10^{10}$ m^{-3} at the time of closest approach to Dione. The new INMS findings confirm indications by the Cassini Plasma Spectrometer [1] and Magnetometer [2] from more distant Dione encounters in 2005 and 2010 of a possible exosphere at Dione, and compliment the recent discovery of an O_2 – CO_2 exosphere at Rhea [3], where O_2 formed in the surface ice by H_2O dissociation and radiolysis reactions reactions is sputtered from the surface by magnetospheric particles. Exospheric CO_2 may be (i) synthesized from radiolysis involving surface-bound oxygen and endogenic and/or implanted organics, and/or (ii) may be due to escape of primordial CO_2 from the ice.

The presence of exospheres of similar densities and compositions at Dione and Rhea indicate that similar physical processes operate at both moons, since these moons have sufficient mass (1.1 and 2.3 $\times10^{21}$ kg, respectively) to retain an exosphere, and orbit in the inner magnetosphere (at 6.3 and 8.8 R_S), where their surfaces are subject to similar magnetospheric particle fluxes [~9(15), 36(10), 48(73) $\times10^{26}$ eV/s from water group ions, protons and electrons at Dione(Rhea) [4]]. Together with the remote detections of sputter-produced O_2 exospheres at Ganymede and Europa by the Hubble Space Telescope [5], and of CO_2 at Callisto by the Gallileo Near Infrared Mapping Spectrometer [6], the Cassini findings at Rhea and Dione appear to suggest radiolytic exospheres, in particular consisting of oxygen and carbon dioxide, may be ubiquitous around irradiated massive icy objects.

However the Cassini CO_2 meaurements present a puzzle. First, while recent studies from VIMS can find no evidence for a currently active endogenic CO_2 source at Dione [7] or Rhea [8], the presence of a CO_2 abundance similar to that of O_2 at Dione and Rhea does not appear, at first look, to be consistent with radiolysis of the surfaces consisting mostly of H_2O.

Moreover, INMS detected $\sim 2\times10^{10}$ CO_2/m^3 over the Rhea north pole during the 97 km March 2, 2010 flyby, but then did not detect CO_2 during the 72 km January 11, 2011 south polar flyby above an upper limit of 0.7×10^{10} m^{-3}. The Rhea findings are suggestive of possible CO_2 condensation onto the southern latitudes surfaces, which are presently cooling as the Saturn system approaches southern winter. Although such a process could account for a reduction of Rhea's global CO_2 exosphere between the 2010 and 2011 encounters, it cannot by itself explain the finding of significant CO_2 at Dione's equator in late 2011.

Here we present new Monte Carlo simulations of the Dione and Rhea exospheres demonstrating that the Cassini INMS measurements of different north-south CO_2 abundances at Rhea, and significant CO_2 at Dione, are consistent with strongly seasonal CO_2 exospheres at these moons. The exospheres are expected to form transient CO_2 polar frosts that migrate seasonally between northern and southern latitudes. The O_2 component is, to a lesser degree, also seasonal.

Exospheric Evolution: We model the exospheres via a Monte Carlo code by tracking the ballistic trajectories of molecules ejected from random surface locations at speeds chosen according to a mixed sputter / Maxwell-Boltzmann distribution [3]. Molecules are allowed to escape gravitationaly, and are destroyed randomly in flight at a rate given by the expected molecule ionization rates by plasma interactions, i.e., photo-ionization, ion and electron impact ionization, and charge exchange, based on laboratory cross sections. On re-impacting the surface, molecules are allowed to stick for time approximated by a Boltzmann factor, i.e., $C^*\exp(E / kT)$, with E the laboratory measured binding energy for O_2 and CO_2 to a smooth substrate (x and x, respectively), T the local surface temperature based on Cassini CIRS data [9] adjusted for the local time and solar declination, and the prefactor C is an adjustable model parameter. After sticking the molecules are allowed to desorb in random directions with speeds initialized according to a Maxwell-Boltzmann distribution at the local surface temperature. The simulation is initially run over several Saturn seasonal cycles to ensure steady-state.

The seasonal evolution of the CO_2 exosphere is shown in Fig. 2 during the 2002-2032 time frame. At solstice the CO_2 condenses at polar latitudes in the winter hemisphere. Then as equinox approaches the CO_2 frost gradually desorbs as the solar terminator advances poleward, heating the frost cap. The desorbed CO_2 forms a transient atmosphere over the dayside hemisphere, which simulataneously adsorbs onto the opposite pole. A few years past equinox (which most recently occurred August 11, 2009) the CO_2 completes the transition between poles, and the atmospheric density rapidly collapses in ~1 (earth) year. The cycle repeats, forming a transient dayside atmosphere every half-season, i.e., every 14.7 years.

In Fig. 2 we compare the modeled density along Cassini's trajectory to the INMS measurement during the Rhea 2010 and 2011 flybys, and the Dione 2011 encounter. The agreement with the data provides an explanation for the north-south difference at Rhea during the 2010-2011 time frame. While in the north the a CO_2 density is elevated due to ougassing of condensed CO_2 from the previous winter, the CO_2 density in the south is suppressed because the south was depleted of CO_2 frost due to the still recently ended southern summer. Thus the CO_2 source was concentrated in the north at the times of the encounters. As shown at Dione the northern latitudes were still outgassing significant CO_2, and therefore the detected Dione CO_2 abundance is consistent with the closer proximity of the equatorial flyby to the gas source in the north (i.e., in comparison to the Rhea 2011 south polar encounter).

We also note that the model only requires source CO_2 source rates of $\sim 9\times10^{21}$ and $\sim 7\times10^{20}$ s^{-1} at Dione and Rhea, respectively, which is much lower than, e.g., the estimated rate of H_2O sputtering from their surfaces (of the order 10^{25} s^{-1} [10]), and the O_2 formation rates (of the order 10^{24} s^{-1} [3]). However the model suggests that the average CO_2 molecule spends over 99% percent of its life stuck to the surface, which drastically reduces the opportunity for escape into space. Therefore we can attribute the significant CO_2 abundance to the low rate of atmospheric escape (due to surface sticking), rather than a high source rate. Such a low source rate would be consistent with a radiolytic CO_2 source, e.g., from a mostly water ice surface, containing a small fraction of carbonaceous material either endogenic to the moon and/or deposited by micrometeorite impact.

Figure Captions: **Fig 1**: INMS measurement of O_2 and CO_2 in mass channels 32 and 44 amu during the 2011 Dione flyby. **Fig 2**: Simulated time evolution of Rhea's CO_2 exosphere.

References: [1] R. L. Tokar *et al.*, Journal of Geophysical Research, in press (2012). [2] S. Simon, J. Saur, F. M. Neubauer, A. Wennmacher, and M. K. Dougherty, Journal of Geophysical Research **38**, L15102 (2011). [3] B. D. Teolis *et al.*, Science **330**, 1813 (2010). [4] M. F. Thomsen *et al.*, Journal of Geophysical Research, in press (2010). [5] D. T. Hall, P. D. Feldman, M. A. McGrath, and D. F. Strobel, Astrophysical Journal **499**, 475 (1998). [6] R. W. Carlson, Science **283**, 820 (1999). [7] K. Stephan *et al.*, Icarus **206**, 631 (2010). [8] K. Stephan *et al.*, Planetary and Space Science, in press (2012). [9] C. J. A. Howett, J. R. Spencer, J. Pearl, and M. Segura, Icarus **206**, 573 (2010). [10] R. E. Johnson *et al.*, Planetary and Space Science **56**, 1238 (2008).

Figure 1

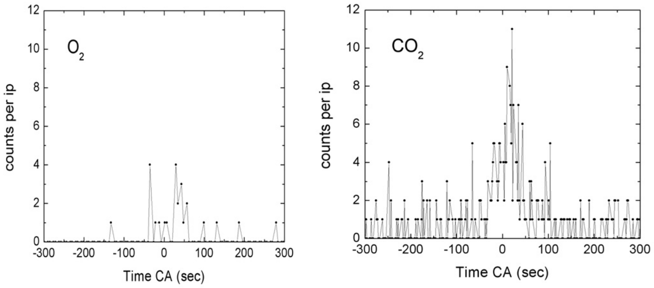

Figure 2