SEARCH FOR CARBON DIOXIDE IN SATURN'S RINGS USING THE *CASSINI* MISSION VISUAL AND INFRARED MAPPING SPECTROMETER (VIMS). J.-Ph. Combe[1], T. B. McCord[1], T. V. Johnson[2], S. Rodriguez[3], [1]Bear Fight Institute (22 Fiddler's Road, PO Box 667,Winthrop WA 98862, United Stated of America, jean-philippe_combe@bearfightinstitute.com), [2]Jet Propulsion Laboratory-California Institute of Technology, Pasadena, CA, United Stated of America, [3]Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Univ Paris Diderot, UMR 7154 CNRS, Paris, France.

Introduction: Carbon dioxide may exist in the main rings of Saturn, according to the results from two experiments of the *Cassini* space mission studying Saturn's magnetosphere [1] and atmosphere [2]. However, to date, no direct CO_2 detection has been made in the rings, which consist of particles with an H_2O ice-rich surface. This study is focused on the search of CO_2 absorption bands in near-infrared reflectance of Saturn's rings measured by the Visual and Infrared Mapping Spectrometer (VIMS) [3].

Background: Possible CO_2 in Saturn's rings coming from Enceladus.

CO^+ and C^+ in Saturn's magnetosphere [1]. CO^+ and C^+ were detected in Saturn's magnetosphere by the Magnetospheric Imaging Instrument (MIMI) and the Charge Energy Mass Spectrometer (CHEMS) [4] of the *Cassini* mission and were interpreted as CO_2 possibly coming from Enceladus. An excess recorded between the late part of 2013 and the end of 2015, with a maximum in September 2014, could be explained by seasonal variations due to a temporary accumulation near spring equinox [1] (which occurred on August 10, 2009, as pictured in Fig. 1) when the temperature of the rings reached a minimum (45-50 K for the A ring and the outer B ring) [5], followed by "a release from the north side of the A, and possibly B, rings as they were warming up above 80 K in late 2013 or early 2014 by increasing solar illumination" [1].

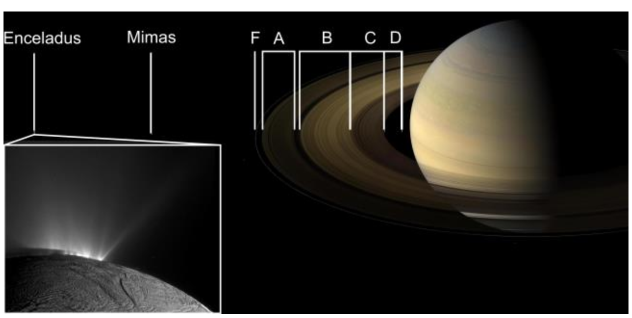

Fig. 1: View of Saturn's rings during the spring equinox by the Imaging Science Subsystem (ISS) of the *Cassini* spacecraft 20°above the ring plane on August 12, 2009. The low solar illumination (illustrated by the faint rings with respect to Saturn) and temperature of the rings' particles could be favorable for the build-up of CO_2 coming from Enceladus[1]. Labels indicate the location of Saturn's main rings and the orbits of Mimas and Enceladus. Lower-left panel: Enceladus plumes from eruptions of the South Polar region [6, 7, 8]. © NASA/JPL/Space Science Institute.

CO_2 raining between the rings and Saturn [2]. During the ring plane crossings of the final orbits of the *Cassini* spacecraft, a compound with 44 atomic mass units (amu) – consistent with CO_2 – was detected by the Ion Neutral Mass Spectrometer (INMS). The highest relative abundances were measured at the highest altitudes above Saturn, compatible with an origin from the rings [2].

CO_2 detected in Enceladus plumes and on its surface. CO_2 was detected on the surface of several icy satellites of Saturn, such as Phoebe [9], Iapetus [10], Enceladus [11] and Hyperion [12, 13]. CO_2 releases from Enceladus may come from plume eruptions [14, 15] or gas pocket eruptions on the south polar region [15, 16, 17]

No claimed CO_2 detection in Saturn's rings from near-infrared spectroscopy.

CO_2 absorption bands were searched for in Saturn's rings using ground telescopic observations in 2000 [18], and then in VIMS spectra [19, 20], well before the equinox of 2014, with no detection. Although spectra shown in Cuzzi et al. (2009) [19] exhibit spectral features at 4.26 µm, no CO_2 detection was reported, possibly because of measurement uncertainties and random instrumental noise. A more recent study [21] using VIMS spectra acquired after the equinox, however, involved no specific search for CO_2.

Analysis of VIMS spectra:

Search for a CO_2 absorption band near 4.26 µm.

The focus of this study is a search for an absorption band in the range 4.24-4.30 µm due to the asymmetric stretching mode of the CO_2 molecule. The VIMS dataset is processed with the RC19 calibration available with the Integrated Software for Imagers and Spectrometers (ISIS). For this study, the correction for wavelength shifting as function of time [22] is performed under the assumption that variations are negligible within the timeframe of a given orbit, in order to be able to calculate statistics on VIMS spectra without the need to resample them. Since the rings composition varies radially [e.g. 13, 21], average spectra of each of the main rings (A, B, C and D, Fig. 2) over all longitudes are calculated for each orbit separately, using the distance to Saturn and illumination conditions (avoiding Saturn's shadow) computed with SPICE data and programs [23] adapted for the rings [e.g. 24] as a discrimination parameter. Preliminary results to date, obtained by scaling the spectra (to minimize the photometric effects) and ratioing to the average [15] did not reveal any CO_2 absorption bands near 4.26 µm in Saturn's rings.

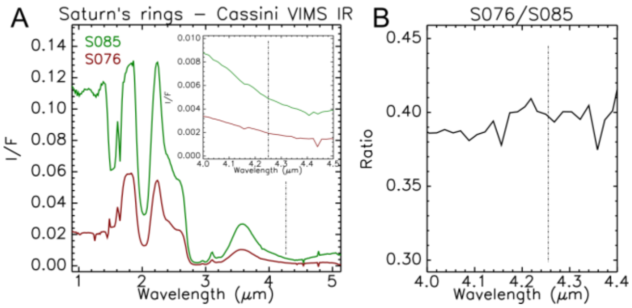

Fig. 2: A. VIMS spectra of Saturn rings averaged over tens of thousands of spectra in order to optimize the signal-to-noise ratio for *Cassini* orbits S076 (near equinox) and orbit S085 (near the maximum of CO^+ and C^+ abundances measured by MIMI/CHEMS). – B. Ratio of the two average spectra of S076 and S085: To date, no CO_2 absorption band has been detected at 4.26 µm, which wavelength is indicated by a vertical line.

Quantifying the abundance of CO_2 in the rings.

In this study, the analysis of CO_2 absorption bands in VIMS spectra will be used to evaluate an upper limit to the amount of CO_2 in the rings by means of radiative transfer modeling and optical constants of H_2O [25] and CO_2 [26, 27] in the range of VIMS wavelength. CO_2 in Saturn's rings could exist as isolated particles between the H_2O ice particles, or as a coating of the H_2O ice particles, or intimately mixed with H_2O ice in the bulk of particles. All these hypotheses can be modeled by adopting assumptions of the Mie theory [28, 29].

Implications and discussion: Origin and age of Saturn's rings.

The particles in Saturn's rings are mostly made of H_2O ice [30, 31], however their photometric properties and near-UV-visible spectra are not consistent with pure H_2O ice and have opened suggestions of organic molecules and iron-rich minerals [32-35]. A recent study by microwave remote sensing revealed that they may consist of a silicate core and an H_2O ice mantle [36]. The rings particle may be debris from a larger object that was destroyed by Saturn's tidal forces. If that is the case, the nature and proportion of non-icy material today can help estimate the rings' exposure age due to micrometeoroid bombardment [37]. The age of Saturn's rings may be ≲150 Myr old [38].

Carbon dioxide is a molecule that is important to study because it may be the origin of certain organic molecules in Saturn's system. CO_2 may have been among the early condensates that were incorporated in the bulk of some of the icy satellites of Saturn during the accretion process, as for the satellites of Jupiter [39]. Today, CO_2 may still be synthesized chemically when a source of energy is available [e.g. 40] or be a product of radiolysis [41, 42]. An expected outcome of constraining the abundance of CO_2 in Saturn's rings will be to provide a way to help understanding their origin, formation process, evolution, and age.

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