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Enceladus' near-surface CO_2 gas pockets and surface frost deposits

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ABSTRACT

Solid CO_2 surface deposits were reported in Enceladus' South Polar Region by Brown et al. (2006). They noted that such volatile deposits are temporary and posited ongoing replenishment. We present a model for this replenishment by expanding on the Matson et al. (2012) model of subsurface heat and chemical transport in Enceladus. Our model explains the distributions of both CO_2 frost and complexed CO_2 clathrate hydrate as seen in the *Cassini* Visual and Infrared Mapping Spectrometer (VIMS) data. We trace the journey of CO_2 from a subsurface ocean. The ocean-water circulation model of Matson et al. (2012) brings water up to near the surface where gas exsolves to form bubbles. Some of the CO_2 bubbles are trapped and form pockets of gas in recesses at the bottom of the uppermost ice layer. When fissures break open these pockets, the CO_2 gas is vented. Gas pocket venting is episodic compared to the more or less continuous eruptive plumes, emanating from the "tiger stripes", that are supported by plume chambers. Two styles of gas pocket venting are considered: (1) seeps, and (2) blowouts.

The presence of CO_2 frost patches suggests that the pocket gas slowly seeped through fractured, cold ice and when some of the gas reached the surface it was cold enough to condense (i.e., $T \sim 70$ to ~ 119 K). If the fissure opening is large, a blowout occurs. The rapid escape of gas and drop in pocket pressure causes water in the pocket to boil and create many small aerosol droplets of seawater. These may be carried along by the erupting gas. Electrically charged droplets can couple to the magnetosphere, and be dragged away from Enceladus. Most of the CO_2 blowout gas escapes from Enceladus and the remainder is distributed globally. However, CO_2 trapped in a clathrate structure does not escape. It is much heavier and slower moving than the CO_2 gas. Its motion is ballistic and has an average range of about 17 km. Thus, it contributes to deposits in the vicinity of the vent. Local heat flow indicates that gas pockets can be located as deep as several tens of meters below the surface. Gas pockets can be reused, and we explore their life cycle.

1. Introduction

CO_2 is present on the surfaces of a number of outer Solar System icy bodies, starting with the icy Galilean satellites (McCord et al., 1997, 1998) and in a thin atmosphere around Callisto (Carlson, 1999). The wavelength of the spectral band center of CO_2 ice on these satellites (Fig. 1) is shorter than expected for pure crystalline or amorphous CO_2 ice and is interpreted (based on laboratory spectra) as being produced by CO_2 molecules in a solid form that is small enough not to allow rotational modes. Pure CO_2 on these bodies should sublimate on rapid geologic timescales, suggesting the CO_2 may be complexed with other materials on their surfaces. Hydrated and amorphous water have been suggested as possible hosts as well as carbon bearing materials (McCord et al., 1998). Furthermore, CO_2 can be present as clathrate hydrate, most likely as Type I, in which 46 water molecules form a cage around the CO_2 (Bollengier et al., 2013; Miller, 1985).

CO_2 has been identified in the spectra of many of Saturn's satellites (Brown et al., 2006; Clark et al., 2005, 2008; Cruikshank et al., 2010), and is interpreted as being complexed in other materials. Early in the *Cassini* mission a possible identification of pure CO_2 ice in a few Visible-Infrared Mapping Spectrometer (VIMS) spectra of Enceladus were reported by Brown et al. (2006). Traces of CO_2 ice were "…found in small amounts globally and in higher concentrations near Enceladus' south polar regions…." (Brown et al., 2006, p. 1427). They noted that CO_2 ice sublimes, and that over the long term the CO_2 deposits would disappear. Thus, they proposed that the CO_2 deposits were recently emplaced. This implies

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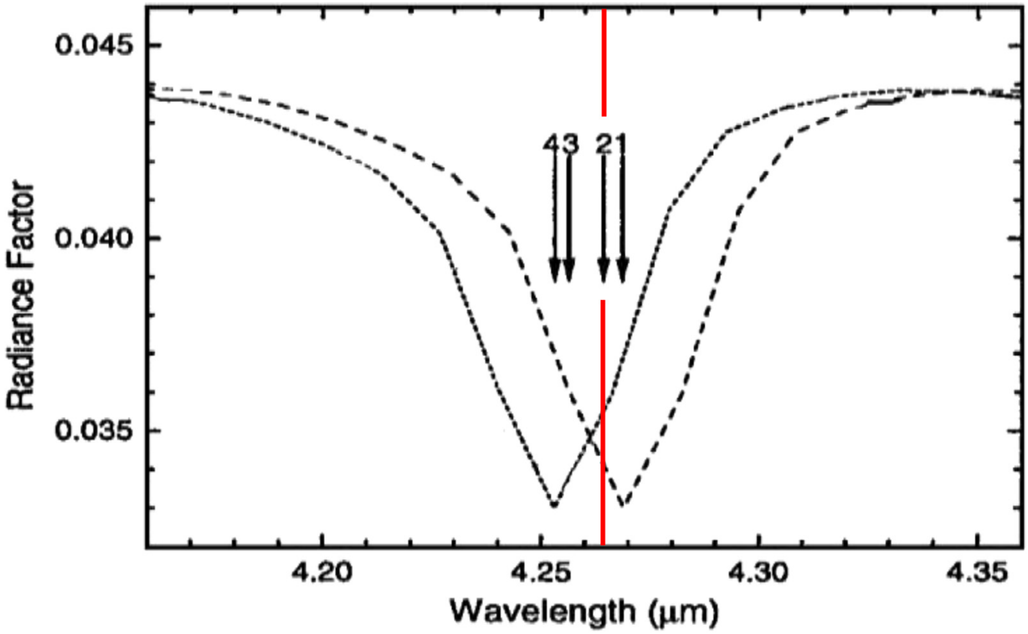

Fig. 1. Position of the 4.25 μm absorption band for CO_2 ice in the following forms: (1) amorphous; (2) crystalline; (3) dispersed in a solid N_2 matrix at 10 K; and (4) as observed on the jovian satellite Callisto by the Galileo Near Infrared Mapping Spectrometer (NIMS). (This figure is modified from Fig. 11 in McCord et al. (1998).) The red line denotes the boundary between complexed and non-complexed CO_2. To the left of the red line, CO_2 is in complexed form. To the right it is in non-complexed form. Combe et al. (Combe et al., 2015, 2017) find CO_2 in both complexed and non-complexed forms on Enceladus. The relatively short residence time of crystalline and amorphous CO_2 on Enceladus requires ongoing replenishment. The dashed curve is generated by the Beer's law absorption of a slab of CO_2 ice, and the dotted curve is the same spectrum shifted by −0.016 μm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that CO_2 gas has been recently vented, which, in turn, raises the questions of from where it originates and the mechanism by which it reaches the surface.

In this paper we propose and investigate a mechanism by which CO_2 can be supplied from subsurface gas pockets associated with the active South Polar Region of Enceladus. These pockets are a natural consequence of the circulation of Enceladus' gas-rich ocean water (Matson et al., 2012). We then examine a detailed mapping of absorption features on Enceladus' surface (Combe et al., 2015, 2017). Finding several forms of CO_2 present, ranging from complexed to free CO_2 ice, as well as mixtures of the two (Combe et al., 2015, 2017).

1.1. CO_2 stability on Enceladus

Early work on the stability of volatiles in the Solar System predicted a CO_2 loss rate of 1–5 cm per year for surface frost or ice at Saturn's distance from the sun (Lebofsky, 1975; Watson et al., 1963). Subsequently, a detailed study of Iapetus by Palmer and Brown (2011) considered the stability and ballistic transport of CO_2 about the satellite. They confirmed the 5 cm per year loss rate for equatorial deposits, but found that CO_2 reaching polar cold traps could be sequestered for up to 15 years before being lost to space. This longer persistence resulted from a model calculation that also included the ballistic transport of evaporated molecules and accounted for those that returned to the polar deposits. If we scale this by relative escape velocity (i.e., Iapetus 573 m/s; Enceladus 239 m/s), the corresponding retention time for Enceladus is about 6 years.

1.2. Enceladus' cryovolcanism

Enceladus is the sixth-largest moon of Saturn. At 500 km in diameter, it was long thought to be too small to be geologically active today, even though *Voyager* images revealed a geologically young surface with smooth, apparently recently-resurfaced regions (Sakurai, 1980; Smith et al., 1982). The *Cassini* spacecraft arrived at Saturn in 2004 and discovered that the South Polar Region of Enceladus had erupting plumes (Dougherty et al., 2006; Hansen et al., 2006; Porco et al., 2006; Spahn et al., 2006). The plumes were composed primarily of water vapor, ice particles, ~5% CO_2, and trace amounts of other gases (Spahn et al., 2006; Waite et al., 2006, 2009).

The South Polar Region has complex fissure-like features (e.g., "Tiger Stripes") that infrared observations show to have warm thermal anomalies that radiate more than ~ 4.7 GW of power (Goguen et al., 2013; Howett et al., 2010, 2013; Spencer et al., 2013, 2006). These anomalies have local "hot" spots where temperatures may reach ~200 K (Goguen et al., 2013). This temperature is about 100 degrees hotter than is possible by heating solely with absorbed sunlight. Furthermore, the Cosmic Dust Analyzer (CDA) onboard *Cassini* found that some of the tiny aerosol particles lofted in the plumes contained salts, including NaCl. This discovery and other evidence led Postberg et al. (2009, 2011) to conclude that the erupting material came from "seawater," suggesting that the composition of the subsurface ocean water is similar to terrestrial seawater. Accordingly, we adopt the properties of seawater as those for our model ocean water. (For background the reader is referred to reviews by Spencer and Nimmo (2013) and Postberg et al. (2016)).

What is the source of the power for operating the present day eruptive plumes and supplying the large amount of energy emitted by the thermal anomalies? Supplying this energy is a major challenge for models of the satellite's thermal history. One possibility is that our understanding of the structure and rheology of these bodies is incomplete (e.g., example discussed by Kieffer et al. (2006)) and that present day tidal heating is much more effective than expected. Movement of the crust from tidal forces could induce shear heating (Nimmo et al., 2007). Another possibility is that the Saturnian satellites formed very early in the lifetime of the Solar System when short-lived radioactive species (e.g., ^{26}Al, ^{60}Fe) could be