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Impact craters: An ice study on Rhea

Cristina M. Dalle Ore [a,b,*], Dale P. Cruikshank [a], Rachel M.E. Mastrapa [a], Emma Lewis [c], Oliver L. White [a]

[a] NASA Ames Research Center, Moffett Field, CA 94035-1000, United States
[b] Carl Sagan Center, SETI Institute, 189 Bernardo Ave., Mountain View, CA 94043, United States
[c] Swarthmore College, 500 College Avenue, Swarthmore, PA 19081, United States

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ABSTRACT

The goal of this project is to study the properties of H_2O ice in the environment of the Saturn satellites and in particular to measure the relative amounts of crystalline and amorphous H_2O ice in and around two craters on Rhea. The craters are remnants of cataclysmic events that, by raising the local temperature, melted the ice, which subsequently crystallized. Based on laboratory experiments it is expected that, when exposed to ion bombardment at the temperatures typical of the Saturn satellites, the crystalline structure of the ice will be broken, resulting in the disordered, amorphous phase. We therefore expect the ice in and around the craters to be partially crystalline and partially amorphous.

We have designed a technique that estimates the relative amounts of crystalline and amorphous H_2O ice based on measurements of the distortion of the 2-μm spectral absorption band. The technique is best suited for planetary surfaces that are predominantly icy, but works also for surfaces slightly contaminated with other ices and non-ice components. We apply the tool to two areas around the Inktomi and the Obatala craters. The first is a young impact crater on the leading hemisphere of Rhea, the second is an older one on the trailing hemisphere.

For each crater we obtain maps of the fraction of crystalline ice, which were overlain onto Imaging Science Subsystem (ISS) images of the satellite searching for correlations between crystallinity and geography. For both craters the largest fractions of crystalline ice are in the center, as would be intuitively expected since the 'ground zero' areas should be most affected by the effects of the impact. The overall distribution of the crystalline ice fraction maps the shape of the crater and, in the case of Inktomi, of the rays. The Inktomi crater ranges between a maximum fraction of 67% crystalline ice to a minimum of 39%. The Obatala crater varies between a maximum of 51% and a minimum of 33%.

Based on simplifying assumptions and the knowledge that crystalline ice exposed to ion bombardment transforms into amorphous at a known rate, we estimate the age of the Obatala crater to be ~450 Ma.

1. Introduction

With the exception of Titan, most saturnian satellites present surfaces rich in H_2O ice, deduced from the characteristic spectral signature in the near-infrared (1–5 μm). The 1.65-μm H_2O ice band, seen in both ground-based spectra and in data from the Cassini Visible-Infrared Mapping Spectrometer (VIMS), indicates the presence of the hexagonal crystalline form. This diagnostic band can be quite prominent in the case of a mixture of crystalline and amorphous ice if the fraction of crystalline is as little as 20% (Mastrapa et al., 2008). The simultaneous presence and relative amounts of the two phases can be deduced from the positions of the broad 1.5- and 2.0-μm bands, but most obviously by the strength of the 1.65-μm band. Another diagnostic is the shape, position, and even the presence of the Fresnel reflectance peak at 3.1 μm (Mastrapa and Brown, 2006), a spectral feature characteristic of crystalline H_2O ice. The temperatures of the surfaces of Saturn's icy satellites are in the range where the amorphous phase is stable over the age of the Solar System (Mastrapa et al., 2013), while the spectral evidence shows the presence of a significant fraction of the crystalline phase.

When crystalline ice is irradiated by photons sufficiently energetic to dissociate the molecule, H_2O molecules are broken into H and OH. By diffusion and recombination through the solid, H atoms disrupt the crystalline structure ultimately resulting in amorphous ice (Baragiola, 2003). Laboratory studies of ice amorphization by ion irradiation in cometary environments have been reported by Strazzulla et al. (1991), and according to Lepault

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[*] Corresponding author at: NASA Ames Research Center, MS 245-6, Moffett Field, CA 94035-1000, United States. Fax: +1 (650) 604 6779.

E-mail address: Cristina.M.DalleOre@nasa.gov (C.M. Dalle Ore).

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et al. (1983) and Heide (1984), electron irradiation can amorphize H_2O ice, but only at $T < 60$ K.

Opposite the amorphization of crystalline ice by irradiation, the reverse process can also occur in some cases when an amorphous sample is irradiated at $T \sim 13$ K by MeV protons (Moore and Hudson, 1992) or at higher temperatures by a high dose of electrons (Dubochet et al., 1982). This process appears to depend on H_2 gas released by the incident radiation, and probably only occurs at shallow depths to which the radiation can penetrate. A phase change from amorphous to crystalline may also occur as a result of localized heating of the ice by impacts of meteoroids in some circumstances (Stewart et al., 2008), and probably by micrometeoroids, although the latter process remains to be observed and quantified in the laboratory. Micrometeorite dust in the outer Solar System may contribute to annealing amorphous icy surfaces (Porter et al., 2010); the number density of small dust particles in the outer Solar System is currently being measured by the New Horizons spacecraft.

Because conversion of the amorphous to the crystalline phase and the reverse on an icy planetary surface is dependent on the environmental factors noted above (temperature changes, irradiation by photons and ions, and micrometeoroid impacts), it is useful to evaluate the relative fractions of these two main phases coexisting in different regions of the Solar System. The proportions of the two phases can be a key to understanding both the present environmental conditions, as well those conditions in the past, insofar as the proportions can be distinguished and measured in regions of differing ages on a planetary surface.

The Cassini VIMS instrument (Brown et al., 2004) has provided numerous hyperspectral image cubes of Saturn's icy satellites, yielding surface spatial resolution better than 10 km/pixel in some cases. While VIMS covers a spectral range that includes several absorption bands of H_2O ice, the important band at 1.65 μm is interrupted by an instrumental effect (an optical filter junction). The ice band at 2.0 μm, however, shows variations in shape and central wavelength that depend on the relative amounts of amorphous and crystalline phases present (Mastrapa et al., 2008), as well as additional effects of grain size and temperature. In this work we use a technique that models the asymmetry of the 2.0-μm H_2O ice band to derive the relative amounts of crystalline and amorphous ice on the surface of Rhea. It removes, with customized calibration curves, the effect of different grain sizes and temperature. To test the technique, we map the ice phase on and around two craters; the relatively young Inktomi crater on the leading hemisphere of Rhea, and the older Obatala crater on the opposite (trailing) hemisphere.

While the *height* of the Fresnel peak is susceptible to the presence of amorphous versus crystalline ice, this parameter is also sensitive to composition and mildly to grain size (Hansen and McCord, 2004). Accurate modeling of this spectral region is therefore required to disentangle the various contributions and has not yet been performed for lack of accurate optical constants in this part of the spectrum. The *position* of the Fresnel peak is also affected by ice phase, but in a more drastic way where the peak shifts toward shorter wavelengths when the ice is mostly (>75%) amorphous (Mastrapa et al., 2009).

While the effects of large impacts on the ice phase at low temperatures (the Stewart et al., 2008 experiments were conducted at 165 K) have not been fully studied in the laboratory, it is expected that the abrupt change in temperature due to the energy delivered by the impactor will trigger melting and an ice phase change that will result in the crystallization of H_2O ice in and around the resulting crater (Baragiola et al., 2013) due to the fact that the liquid H_2O freezes at a temperature higher than the original temperature of the ice. The position of Rhea relative to Saturn makes it the target of ion, electron, and particle bombardment from the magnetosphere and the E-ring, and its heavily cratered surface demonstrates that it has also been the target of large-scale impacts over much of the age of the Solar System. While large-scale impacts produce crystalline ice, the bombardment of the surface by charged particles and micrometeoroids should, on the basis of laboratory studies cited above, result in a significant fraction of the amorphous phase. Thus, a map of the relative abundances of crystalline and amorphous ice in and around a crater can provide a test of the laboratory knowledge of the behavior of H_2O ice. Furthermore, in favorable cases and with some simplifying assumptions, this information can give a rough estimate of the age of the crater.

2. Data description

The observations adopted for this study were obtained with the Cassini's Visual and Infrared Mapping Spectrometer (Brown et al., 2004) during two flybys of Rhea in August 2007 and November 2009. Table 1 lists some of the observing circumstances for the data cubes.

The cubes were selected based on a few criteria that provided the data quality needed for the measurements. We made our selection based on the best available spatial resolution (small pixel scale) to resolve geographical features whenever possible, a small phase angle to limit the effects of illumination on the spectral shape, and adequate geographical coverage of the chosen craters. The data were radiometrically calibrated to convert the observed DNs (raw data numbers) in reflectance (I/F) making use of the latest (RC17) response function (Brown et al., 2004). The cubes have a ground resolution (pixel scale) of ~4 and 6 km respectively allowing for a well-detailed map of the craters. Phase angles <60° limit the effect of shadows on the illumination of the craters.

The spectral sampling interval of the cubes is 0.016 μm in the infrared spectral region of our study that includes the 1.5 and 2.0 μm H_2O ice absorption bands.

3. Background on methodology and technique

Grundy and Schmitt (1998) in their rigorous study of crystalline H_2O ice spectral behavior in the near-infrared showed that the 1.5- and 2.0-μm bands can be fitted with a few Gaussians with different widths and positions. While the 1.5-μm band is a combination of at least five Gaussians, the 2.0-μm band is composed of three, of which one is predominant in its contribution to the total absorption. Variations in ice phase affect the relative strength of the Gaussians that compose the 2.0-μm band (Mastrapa et al., 2008), particularly the two secondary ones, ultimately yielding asymmetries in the shape of the band.

Based on the work by Grundy and Schmitt (1998) we have adopted a new technique that quantifies the 2.0-μm band asymmetry to determine the fraction of crystalline to amorphous ice on the surface. In our calculations we made use of a code based on the Shkuratov et al. (1999) formulation of the slab

Table 1
Observing circumstances for the two cubes adopted in this study.

Crater	Cube	Obs ID Start time	Pixel scale (km/px)	Phase angle (°)
Inktomi	CM_1567132446_1.cub	VIMS_049RH_RHEA010 2007-08-30T08:59:12Z	4.3	29.1
Obatala	CM_1637518833_1.cub	VIMS_121RH_RHEA014 2009-11-22T01:37:22Z	6.1	55.4