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Distribution of CO_2 ice on the large moons of Uranus and evidence for compositional stratification of their near-surfaces

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ABSTRACT

The surfaces of the large uranian satellites are characterized by a mixture of H_2O ice and a dark, potentially carbon-rich, constituent, along with CO_2 ice. At the mean heliocentric distance of the uranian system, native CO_2 ice should be removed on timescales shorter than the age of the Solar System. Consequently, the detected CO_2 ice might be actively produced. Analogous to irradiation of icy moons in the Jupiter and Saturn systems, we hypothesize that charged particles caught in Uranus' magnetic field bombard the surfaces of the uranian satellites, driving a radiolytic CO_2 production cycle. To test this hypothesis, we investigated the distribution of CO_2 ice by analyzing near-infrared (NIR) spectra of these moons, gathered using the SpeX spectrograph at NASA's Infrared Telescope Facility (IRTF) (2000–2013). Additionally, we made spectrophotometric measurements using images gathered by the Infrared Array Camera (IRAC) onboard the Spitzer Space Telescope (2003–2005). We find that the detected CO_2 ice is primarily on the trailing hemispheres of the satellites closest to Uranus, consistent with other observations of these moons. Our band parameter analysis indicates that the detected CO_2 ice is pure and segregated from other constituents. Our spectrophotometric analysis indicates that IRAC is not sensitive to the CO_2 ice detected by SpeX, potentially because CO_2 is retained beneath a thin surface layer dominated by H_2O ice that is opaque to photons over IRAC wavelengths. Thus, our combined SpeX and IRAC analyses suggest that the near-surfaces (*i.e.*, top few 100 μm) of the uranian satellites are compositionally stratified. We briefly compare the spectral characteristics of the CO_2 ice detected on the uranian moons to icy satellites elsewhere, and we also consider the most likely drivers of the observed distribution of CO_2 ice.

1. Introduction

Spatially resolved images gathered by the Imaging Science System (ISS) onboard Voyager 2 revealed that the surfaces of the classical (*i.e.*, large and tidally-locked) uranian satellites Miranda, Ariel, Umbriel, Titania, and Oberon (Table 1) are grayish in tone, with bright patches generally associated with impact features and tectonized terrain (*e.g.*, Smith et al., 1986). Analysis of ISS images demonstrated that the uranian satellites' leading hemispheres are spectrally redder than their trailing hemispheres, and the amount of reddening appears to increase with increasing distance from Uranus (Bell and McCord, 1991; Buratti and Mosher, 1991; Helfenstein et al., 1991). These satellites display abundant evidence of tectonic resurfacing, ranging from tectonized coronae and chasmata on Miranda (*e.g.*, Pappalardo et al., 1997; Beddingfield et al., 2015) to subtle polygonal basins observed on Umbriel (Helfenstein et al., 1989). Numerous studies have presented evidence for potential cryovolcanic landforms on each of these moons, from flow bands with medial grooves on Ariel, smooth patches with convex edges on Titania, and smooth, low and high albedo deposits on crater floors on Umbriel and Oberon (*e.g.*, Jankowski and Squyres, 1988; Schenk, 1991; Croft and Soderblom, 1991; Kargel, 1994). Surface age estimates range from a few 100 Ma for younger terrains on Ariel to >4 Ga for most of the ancient surface of Umbriel (Zahnle et al., 2003). Geologic interpretation of these satellites' surfaces, however, is limited by the low spatial resolution of the ISS dataset, ranging from a few 100 m/pixel on Miranda to ~6 km/pixel on Oberon.

While Voyager 2's flyby of Uranus returned a wealth of information (*e.g.*, Stone and Miller, 1986), it is the only spacecraft to visit the uranian system. Consequently, compositional analysis of Oberon, Titania, Umbriel, Ariel, and Miranda is much less-well

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Table 1
Classical uranian satellites.

Satellite	Orbital radius (km)	Orbital radius (R_{Uranus})	Orbital period (days)	Radius (km)	Density (g cm^{-3})	Geometric albedo (~0.957 μm)[a]
Miranda	129,900	5.12	1.41	236	1.21	0.45 ± 0.02
Ariel	190,900	7.53	2.52	579	1.59	0.56 ± 0.02
Umbriel	266,000	10.49	4.14	585	1.46	0.26 ± 0.01
Titania	436,300	17.20	8.71	789	1.66	0.39 ± 0.02
Oberon	583,500	23.01	13.46	762	1.56	0.33 ± 0.01

[a] Geometric albedos digitally extracted from Fig. 7 in Karkoschka (2001).

developed than that of their jovian and saturnian counterparts, which have been imaged extensively by the Galileo and Cassini spacecraft, respectively. Ground-based observations of the large uranian satellites indicate that their surfaces are dominated by H_2O ice mixed with a low-albedo constituent, which is spectrally neutral over NIR wavelengths (*e.g.*, Soifer et al., 1981; Brown and Cruikshank, 1983; Brown and Clark, 1984). Although the low albedo constituent detected on the surfaces of the uranian satellites has yet to be uniquely identified, spectral modeling suggests that it is likely carbon-rich (*e.g.*, Clark and Lucey, 1984).

More recent NIR observations of these moons led to the detection of CO_2 ice on Ariel, Umbriel, and Titania, principally on their trailing hemispheres (Grundy et al., 2003, 2006). Additionally, Grundy et al. (2006) found that the abundance of CO_2 ice decreases with increasing orbital radius, with no detection on the furthest classical satellite, Oberon. A host of loss mechanisms (*e.g.*, sublimation, UV photolysis, micrometeorite bombardment, and charged particle sputtering) should effectively remove CO_2 from their surfaces over timescales shorter than the age of the Solar System (*e.g.*, Grundy et al., 2006). Consequently, the detection of CO_2 on the uranian moons suggests that it is actively produced by non-native processes. Grundy et al. (2006) suggest that bombardment of native H_2O ice and C-rich constituents on the uranian satellite surfaces by magnetospherically-bound charged particles could drive a radiolytic production cycle of CO_2 ice.

Magnetic field interactions with icy satellite surfaces are well documented in the Jupiter and Saturn systems. UV spectra of Europa's trailing hemisphere display an enhanced absorption feature near 280 nm (attributed to SO_2) that likely originated from magnetospherically-embedded sulfur ions irradiating H_2O ice on Europa's surface (Lane et al., 1981; Ockert et al., 1987; Noll et al., 1995). An albedo minimum near 260 nm in UV spectra of Rhea and Dione has been attributed to magnetospherically-generated O_3 trapped in the H_2O ice matrix on these moons' surfaces (Noll et al., 1997). The magnetic fields of Jupiter, Saturn, and Uranus all co-rotate with the planets, and at a faster rate than the orbital periods of their regular moons. Consequently, charged particles caught in these planet's magnetic fields preferentially interact with the trailing hemispheres of their classical satellite systems. Unlike the magnetic fields of Jupiter and Saturn, Uranus' magnetic field is substantially offset from its rotational axis (~58.6°) and from its center of mass (~0.3 uranian radii); modeling interactions between Uranus' moons and its magnetic field is therefore difficult.

In order to test the hypothesis that CO_2 ice on the surfaces of Ariel, Umbriel, Titania, and Oberon is generated by magnetospherically-trapped charged particle irradiation, we have collected new SpeX spectra of these moons' previously unobserved northern hemispheres. Using these spectra, along with two other SpeX datasets collected over their southern hemispheres, and spectrophotometry measured by IRAC, we investigate the spatial distribution and mixing regime of CO_2 ice on these satellites. We also explore the distribution of H_2O ice on these moons. Additionally, the broad wavelength range of the SpeX (~0.81–2.42 μm) and IRAC (~3.1–9.5 μm) datasets enables us to characterize vertical layering in these moons' near-surfaces.

2. Observations and data reduction

2.1. IRTF/SpeX

Observations of the uranian satellites reported in this work were gathered between 2000 and 2013 using the short wavelength cross-dispersed mode (SXD) of the NIR spectrograph/imager SpeX at the IRTF on Mauna Kea, Hawaii (Rayner et al., 1998, 2003). These observations were made by three different teams (summarized in Table 2, mid-observation 'sub-observer' latitudes and longitudes displayed in Fig. 1). The observations by Cartwright and those by Rivkin are presented here for the first time, whereas the data from Grundy were published in Grundy et al. (2003, 2006), and we refer the reader to these publications for details regarding their data reduction procedures. SpeX includes two detectors: a 1024 × 1024 InSb array for the spectrograph (0.15 arcsec/pixel), and a 512 × 512 InSb array that images the slit (0.12 arcsec/pixel). All uranian satellite spectra gathered between 2000 and 2012 have a spectral range of ~0.81–2.42 μm. Data gathered by Cartwright in 2013 utilized the visible/near-infrared (VNIR) MORIS camera co-mounted with SpeX, resulting in a slightly reduced spectral range for those SpeX spectra (covering ~0.94–2.42 μm). Observations made by Rivkin and Cartwright used a 0.8 × 15 arcsec slit, providing spectral resolution ($R = \lambda/\Delta\lambda$) of ~650–750. Grundy et al. (2003, 2006) used two different slit width settings (0.3 × 15 arcsec and 0.5 × 15 arcsec), resulting in spectral resolutions of ~1600–1700 and ~1300–1400, respectively.

For all three SpeX datasets, spectra were gathered as pairs, with the object imaged in two positions (referred to as A and B beams) separated by 7.5 arcsec along the 15-arcsec slit. Subtraction of these A–B image pairs provides first order removal of sky emission. Maximum exposure time per frame was limited to 120 s to minimize sky emission variability. In order to improve the signal to noise ratio (S/N), object frames from each night were co-added during data reduction. Nearby solar analog stars were observed by each team to ensure good correction of atmospheric absorption (summarized in Table 3). These solar analogs were observed repeatedly throughout the observations at multiple airmasses. Flat field images and wavelength calibration files were obtained using observations of SpeX's internal integrating sphere illuminated by a quartz lamp and an argon lamp, respectively.

Background subtraction and extraction of spectra gathered by Rivkin and those gathered by Cartwright were conducted using custom programs and the Spextool data reduction package (Cushing et al., 2004; Vacca et al., 2003). Extracted satellite spectra were divided by solar analog spectra from the same night, at similar air masses. Solar-analog-divided spectra were then combined using custom programs and the Spextool program suite (Cushing et al., 2004). We applied several additional corrections to the spectra gathered by Cartwright in 2012 and 2013 to remove residual telluric contributions, including: sub-pixel shifting of object and solar analog spectra, interpolation of solar analog airmasses to better match object airmasses, and dividing spectra by an appropriately scaled atmospheric transmission spectra (gathered at Mauna Kea). A scaled spectrum of Uranus (Rayner et al., 2009) was used to correct for scattered light in the Ariel and Umbriel