Discovery of CO₂ Ice and Leading-Trailing Spectral Asymmetry on the Uranian Satellite Ariel

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ABSTRACT

New 0.8 to 2.4 \( \mu \text{m} \) spectral observations of the leading and trailing hemispheres of the Uranian satellite Ariel were obtained at IRTF/Spex during 2002 July 16 and 17 UT. The new spectra reveal contrasts between Ariel’s leading and trailing hemispheres, with the leading hemisphere presenting deeper \( \text{H}_2\text{O} \) ice absorption bands. The observed dichotomy is comparable to leading-trailing spectral asymmetries observed among Jovian and Saturnian icy satellites. More remarkably, the trailing hemisphere spectrum exhibits three narrow \( \text{CO}_2 \) ice absorption bands near 2 \( \mu \text{m} \). This discovery of \( \text{CO}_2 \) ice on one hemisphere of Ariel is its first reported detection in the Uranian system.

Subject headings: Ices; satellite surfaces; satellites of Uranus; infrared observations

1. Introduction

Near-infrared spectral differences between leading and trailing hemispheres of tidally-locked Jovian and Saturnian icy satellites have been studied for many years (e.g., Clark et al. 1984; Calvin and Clark 1993). Characteristic features include deeper 1.5 and 2 \( \mu \text{m} \) \( \text{H}_2\text{O} \) ice absorption bands on leading hemispheres and distorted band shapes on trailing hemispheres (e.g., Grundy et al. 1999).

Two processes are thought to be primary causes of the compositional and textural differences which are implied by the observed near-infrared spectral contrasts between leading and trailing hemispheres. First, the orbital motion of tidally-locked satellites around their primary planets results in higher rates of impacts on their leading hemispheres by material from outside the planet-satellite system. Elevated rates of bombardment on leading
hemispheres are compounded by higher mean impact velocities (e.g., Zahnle et al. 2001). Second, charged particles in a planet’s magnetosphere are dragged around the planet by the rotation of its magnetic field. Since the spin periods of giant planets in our solar system are generally shorter than the orbital periods of their major satellites, magnetospheric particles having gyroradii smaller than the satellites tend to impinge on the trailing hemispheres of the satellites (e.g., Pospieszalska and Johnson 1989; Johnson 1990). Both processes are capable of altering the textures and compositions of icy satellite surfaces, and are thought to account for most observed leading-trailing spectral reflectance dichotomies (apart from unusual cases like Iapetus).

In addition to the well-known spectral asymmetries among Jovian and Saturnian icy satellites, tentative evidence has been reported for leading-trailing spectral asymmetries on Neptune’s satellite Triton (Cruikshank and Apt 1984) and Pluto’s satellite Charon (Buie and Grundy 2000; Dumas et al. 2001). However, near-infrared spectral asymmetries have not previously been seen among Uranian satellites. During the previous two decades of infrared spectral observation, the Uranian system had been oriented roughly pole-on to the sun and Earth, making it difficult for Earth-based observers to study leading and trailing hemispheres separately. Sub-solar latitudes in the Uranian system have recently moved to within 20° of the equator, making searches for leading-trailing asymmetries timely.

The first target we selected for this search was the satellite Ariel. Its orbital period of 2.52 days makes nearly opposite hemispheres conveniently observable on consecutive nights. During the 1986 flyby of Voyager 2, only southern latitudes of Ariel could be viewed. Nevertheless, the Voyager images revealed clear differences between Ariel’s leading and trailing hemispheres at visible wavelengths. Younger terrains including bright ejecta deposits were prominent on the southern part of Ariel’s leading hemisphere, while the southern part of the trailing hemisphere featured fewer high-albedo patches and had a
slightly redder visual color (e.g., Smith et al. 1986; Plescia 1987; Buratti and Mosher 1991; Croft and Soderblom 1991; Veverka et al. 1991). Ariel’s 5.5 km s$^{-1}$ mean orbital speed around Uranus is sufficient to cause significant differences between cratering rates on leading and trailing hemispheres (e.g., Zahnle et al. 2001). The Uranian plasma environment is rather peculiar, compared with Jovian and Saturnian magnetospheres, because of Uranus’ very high obliquity and the considerable tilt of Uranus’ magnetic dipole with respect to the planet’s spin axis (e.g., Ness et al. 1986). However, fluxes of energetic protons observed during the Voyager encounter in 1986 are sufficient to drive radiolytic chemistry on time scales much shorter than the age of the solar system (e.g., Bridge et al. 1986; Krimigis et al. 1986; Lanzerotti et al. 1987; Johnson 1990). These factors made a search for spectral dichotomies on Ariel particularly compelling.

2. Observations and Reduction

We observed Ariel during 2002 July 16 11:15-15:08 UT and 2002 July 17 11:51-15:12 UT with the SpeX spectrograph (Rayner et al. 1998) at NASA’s Infrared Telescope Facility (IRTF). Using the short cross-dispersed mode with a 0.5 arcsec slit we recorded five spectral orders, collectively covering the 0.8 to 2.4 μm wavelength range. Total on-target integration time was 140 minutes on July 16 and 112 minutes on July 17, at airmasses between 1.19 and 1.50. Thin cirrus was present both nights. At the weighted mid-times of the observations (13:08 on July 16, 13:29 on July 17), sub-Earth longitudes on Ariel were 294.6° and 79.5° respectively (IAU coordinates). Sub-Earth latitudes were −20° both nights and sun-object-Earth phase angles were 1.65° and 1.60°. Ariel was 20.00 AU from the sun both nights, and approximately 11 arcsec from the limb of Uranus, far enough for scattered light from Uranus to be negligible.

To record background flux without sacrificing on-target exposure time we observed
alternately in two positions (‘A’ and ‘B’) separated by 10 arcsec along the 15 arcsec slit. During our observations, we used an image rotator to orient the slit within 30 degrees of the parallactic angle (the sky-plane projection of the plane defined by observer-object and observer-zenith vectors) to minimize light losses from atmospheric dispersion, taking care to avoid placing Uranus or other moons in the slit. The dispersion caused by the Earth’s atmosphere is less than 0.25 arcsec across the slit and 0.43 arcsec in the along-slit direction for the full spectral range, 0.8 to 2.4 μm. For the primary region of interest, 1.25 to 2.4 μm, the dispersions reduce to 0.10 arcsec cross-slit and 0.17 arcsec along-slit. Because the seeing was approximately 0.7 to 1.0 arcsec on both nights, we do not expect atmospheric dispersion to have introduced appreciable slopes in our extracted spectra.

Spectral extraction was accomplished using the Horne (1986) optimal extraction algorithm as implemented by M.W. Buie at Lowell Observatory (e.g., Buie and Grundy 2000; Grundy and Buie 2002).

Between 0.8 and 2.4 μm, the flux from Ariel is entirely due to reflected sunlight. The solar flux distribution was characterized using solar analogs HD219018, 16 Cyg B, and SA112-1333, observed repeatedly at multiple airmasses. At our wavelength range, spectral resolution, and signal precision, the spectra of these stars are indistinguishable from that of the sun. Telluric extinction was determined from the suite of solar analog observations. All stellar and Ariel spectra were corrected to a common airmass prior to performing the ratio between grand average of Ariel and grand average of all the solar analogs, thus removing the solar flux distribution and the instrumental response function. Residual telluric features remain, primarily near 1.4 and 1.9 μm, where telluric H₂O vapor absorptions make sky transparency especially variable both in time and in wavelength.

Wavelength calibration was derived from regular observations of SpeX’s internal integrating sphere, illuminated by an argon arc lamp. This source provided from 6 to more
than 20 emission lines per spectral order. Dispersion ranged from $2.3 \times 10^{-4} \, \mu m/pixel$ at the shortest wavelengths to $5.4 \times 10^{-4} \, \mu m/pixel$ in the K band. Internal flexure produced shifts of as much as a pixel, resulting in an uncertainty in wavelength calibration of about $\pm 0.5$ pixel. Averaging several arc lamp images together enabled us to determine the effective line spread function for a filled slit for observations spanning a range of positions on the sky. The resulting emission line profiles were well approximated by Gaussians having full width at half maximum (FWHM) of 4 pixels, implying resolving power ($\lambda/\Delta \lambda$) ranging from 870 at 0.8 $\mu m$ to 1100 at 2.4 $\mu m$. With seeing disks uniformly wider than the slit, the filled slit resolution and wavelength uncertainties apply to our observations of solar analogs and Ariel alike. Final, normalized albedo spectra of Ariel for the two nights are shown in Fig. 1.

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3. Discussion

The most prominent features in Ariel’s near-infrared spectrum are water ice vibrational absorption bands at 1.5, 1.56, 1.65, and 2 $\mu m$. Using lower resolution data, these H$_2$O bands have been analyzed previously (e.g., Cruikshank and Brown 1981; Brown and Cruikshank 1983; Grundy et al. 1999). The shapes of the H$_2$O ice bands in our data are consistent with multiple scattering by ice particles in the 10 to 100 $\mu m$ size range, in combination with dark material to reduce the overall albedo. The presence of 1.56 and 1.65 $\mu m$ bands in our data (and also in the data of Grundy et al. 1999) clearly indicates that the H$_2$O is crystalline rather than amorphous, but we cannot determine if it is predominantly hexagonal ice I$_h$ or cubic ice I$_c$. Based on their far infrared spectral behavior, ice I$_h$ is not expected to differ dramatically from ice I$_c$ in the near infrared, (e.g., Bertie and Whalley 1964; Bertie and Jacobs 1977; Grundy et al. 1999), but near infrared laboratory studies of ice I$_c$ have yet to
be published.

The relative strengths and wavelengths of H₂O ice absorption bands have been shown to depend on the temperature of the ice, in addition to the degree of crystallization (e.g., Kieffer and Smythe 1974; Fink and Larson 1975; Grundy and Schmitt 1998). Grundy et al. (1999) made use of this dependence to determine an average ice temperature for Ariel of 59±12 K, based on observations obtained in 1995, when the sub-solar latitude was −50°. Using their technique, we now calculate ice temperatures 71±5 and 70±23 K for leading and trailing hemispheres, respectively. The uncertainty is much higher for the trailing hemisphere not because of any difference in the quality of the data obtained, but apparently because the ice absorption band shapes are not as well fit by simple multiple scattering models making use of optical constants for crystalline H₂O ice. The temperature-sensing technique can be vulnerable to the existence of other phases including radiation-damaged, amorphous ice, as discussed by Grundy et al. (1999). The primary advantage of this technique is its sensitivity to the brightest, coldest H₂O ice, in contrast with thermal emission measurements which are more sensitive to warmer, darker regions.

As seen in Fig. 1, the 1.5 and 2 μm water ice bands are significantly deeper in the 2002 July 17 UT spectrum, compared with that of 2002 July 16. The 1.5 μm band, for example, was about 65% deeper on July 17. The sub-viewer and sub-solar longitudes on July 17 were ∼80°, corresponding approximately to Ariel’s leading hemisphere, which is centered on 90°. On July 16, our ∼295° sub-viewer and sub-solar longitudes were approximately aligned with the opposite, trailing hemisphere, which is centered at 270° longitude. The sub-viewer and sub-solar latitudes on both nights were about −20° (IAU South is oriented in the direction of Ariel’s angular momentum vector), much closer to the equator than has been seen over the previous two decades of infrared observation, making these observations more sensitive to hemispherical differences than observations during the 1980s and 1990s.
Deeper H$_2$O ice bands on leading hemispheres are the norm among icy satellites of Jupiter and Saturn (e.g., Clark et al. 1984; Grundy et al. 1999), so it is not surprising to now discover the same trend on a Uranian satellite. It is not clear if the deeper leading hemisphere H$_2$O bands are due to relatively clean ice being excavated by impacts or if the weaker trailing hemisphere bands are due to charged particle sputtering removal of ice. Lanzerotti et al. (1987) estimated that $\sim$3 $\mu$m of H$_2$O ice could be removed from Ariel’s surface by charged particle sputtering in 10$^7$ years, though it has yet to be established that the plasma measurements made by Voyager 2 are similar to seasonally-averaged fluxes in the Uranian magnetosphere. Ultraviolet sputtering, which would affect leading and trailing hemispheres equally, may be even more efficient at removing H$_2$O from Ariel’s surface, and micrometeorite sputtering, which would predominantly affect the leading hemisphere, may be most efficient of all (e.g., Eviatar and Johnson 1986; Cheng et al. 1991). The observed dichotomy in H$_2$O ice band depths seems most likely to be the result of a combination of impact- and radiation-related processes.

The appearance of three narrow absorption bands at 1.966, 2.012, and 2.070 $\mu$m is more remarkable, since they have not previously been detected on any icy satellite other than Triton (Cruikshank et al. 1993). This triplet can be confidently attributed to absorption by the $2\nu_1+\nu_3$, $\nu_1+2\nu_2+\nu_3$, and $4\nu_2+\nu_3$ transitions in CO$_2$ ice, as shown in Fig. 2 (band identifications from Quirico and Schmitt 1997). Triton’s CO$_2$ bands have been modeled as arising from a mixture of H$_2$O and CO$_2$ ices covering approximately 45% of Triton’s visible hemisphere (Quirico et al. 1999). While the appearance of the CO$_2$ ice triplet near 2 $\mu$m is apparently rare among icy satellites, the much stronger $\nu_3$ fundamental band of CO$_2$ at 4.25 $\mu$m has been detected by the Galileo spacecraft on Jovian satellites Ganymede and Callisto (e.g., McCord et al. 1997, 1998; Hibbitts et al. 2000). The $\nu_3$ band of CO$_2$ ice could well exist in the spectra of many icy satellites, as very little CO$_2$ is required to produce it, but the opacity of telluric CO$_2$ vapor makes this band impossible to detect from Earth-based
observatories. We are only aware of one earlier, unpublished search for CO$_2$ ice absorptions on Uranian satellites. A.S. Rivkin, D.E. Trilling, and R.H. Brown surveyed the Uranian satellites in 1998 using the CGS4 spectrometer at the United Kingdom InfraRed Telescope (A.S. Rivkin, personal communication 2002). Rivkin et al. did not detect CO$_2$, though in light of our results, it appears that their non-detection on Ariel resulted from observing the leading rather than trailing hemisphere (Ariel’s subsolar longitude was approximately 140° at the time of their observations).

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This discovery of CO$_2$ ice on Ariel’s trailing hemisphere doubles the inventory of known ices in the Uranian system. It also raises many interesting questions. For instance, why has CO$_2$ ice only been seen on Ariel and not on the other major Uranian satellites, and why only on the trailing hemisphere, when H$_2$O ice bands are normally deeper on leading hemispheres? How abundant and widespread is it, relative to H$_2$O ice? How long does it survive on Ariel’s surface? What processes act on exposed CO$_2$ ice? Is it a relic of Ariel’s primordial volatile inventory? Was it delivered by more recent impactors? Or is it produced from other materials in chemical reactions enabled by energetic radiation?

The source of Ariel’s CO$_2$ is unknown. Primordial carbon-containing compounds such as methane (e.g., Pollack et al. 1991) could possibly contribute to radiolytic production of CO$_2$ in combination with Ariel’s H$_2$O ice (Delitsky and Lane 1998). Carbonaceous material delivered via impacting dust or larger particles could be another source of carbon. Indigenous CO$_2$ could have been produced in Ariel’s interior during an early tidal heating episode and subsequently erupted onto the surface (e.g., Squyres et al. 1985; Shock and McKinnon 1993). The implantation of carbon ions from the Uranian magnetosphere appears to be a less likely source, as the Voyager spacecraft found almost no ions heavier
than protons during the 1986 flyby (Bridge et al. 1986; Krimigis et al. 1986). However, the seasonal dependence of heavy ion abundances is uncertain.

If radiolysis is producing CO$_2$ from H$_2$O and some source of carbon within Ariel’s surface, or is acting on extant CO$_2$ and H$_2$O ices, other reaction products could be produced as well. Searches for their absorption bands could offer a sensitive probe of the chemical pathways active within Ariel’s surface ices. Additional species one might expect to see include volatiles such as CO and O$_2$, but unless they are trapped within the host water ice (i.e., via hydrogen bonding) these species could relatively quickly escape to space. They could conceivably be detectable in the gas phase, however, if residence times are long enough and production rates are high enough. Less volatile and more chemically interesting candidates to search for include carbon suboxide C$_3$O$_2$ and its polymers (C$_3$O$_2$)$_n$, carbonic acid H$_2$CO$_3$, hydrogen peroxide H$_2$O$_2$, formaldehyde H$_2$CO and its polymer polyoxymethylene, and methanol CH$_3$OH (e.g., Schutte et al. 1993; Gerakines et al. 1996; Brucato et al. 1997; Delitsky and Lane 1997; Johnson and Quickenden 1997; Delitsky and Lane 1998; Gerakines and Moore 2001; Hudson and Moore 2001). Perhaps some of these compounds could survive long enough in Ariel’s near-surface environment to be spectroscopically observable.

The vapor pressure of CO$_2$ ice at our measured H$_2$O ice temperature of 70 K is comparable to that of water ice at 130 K (Brown and Ziegler 1979). Ariel’s darker regions may reach subsolar temperatures approaching 90 K. At these temperatures, CO$_2$ ice should be rapidly transformed (or even removed altogether) by volatile transport processes such as sublimation, grain growth, sintering, and solar gardening (e.g., Clark et al. 1983; Spencer 1987; Grundy and Stansberry 2000). Even at the lower temperatures which prevail in higher albedo regions and away from Ariel’s subsolar point, CO$_2$ ice is considerably more readily mobilized than H$_2$O ice is via charged particle sputtering (e.g., Johnson et al. 1983),
so its longevity at the surface could be relatively brief. Alternatively, Ariel’s CO2 could be trapped within a H2O ice matrix, making it less mobile but more readily available for carbon, oxygen, and hydrogen chemistry. However, if the CO2 were trapped in a H2O matrix, one would expect its absorption bands to shift in wavelength, and normally inactive modes could become activated and produce bands, such as the 2ν3 transition which might be expected to produce a band near 2.14 μm (Schmitt, personal communication 2002). No convincing spectral evidence is seen for CO2 being trapped in H2O. Much additional work is clearly needed to work out the origin and the fate of CO2 on Ariel’s surface.

We generated synthetic spectra with the Hapke model (e.g., Hapke 1993) to estimate the quantity of CO2 ice required by the observed absorptions. Unfortunately, abundances derived from disk-integrated spectral models are extremely dependent on model assumptions. For this reason, it would be imprudent to assign much confidence to any abundance ratio computed from a single model. We tried four different model scenarios to illustrate the influence of model assumptions on computed abundances, using CO2 ice refractive indices n from (G.B. Hansen, personal communication; see Hansen 1997) and absorption coefficients k from Schmitt et al. (1998). In the first model, we simulated a glaze of CO2 ice atop a multiple-scattering mixture of H2O and dark material. The best-fitting thickness of a hemispheric CO2 glaze is about 5 μm; thicker coatings would be required for glazes not covering the entire hemisphere. In our second model, we replaced a fraction of the H2O grains with CO2 ice grains of the same size. Mixing ratios in the neighborhood of H2O:CO2=3:1 produced reasonable fits with this scenario. An alternate mixture disperses the CO2 at the molecular level within H2O by means of a linear combination of optical constants. This scenario yielded a similar mixing ratio of H2O:CO2=4:1. Finally, we tried an areal mixture, in which H2O ice was replaced with CO2 ice on a fraction of Ariel’s trailing hemisphere. In this model (the one shown in Fig. 2), CO2 ice covering 8% of the trailing hemisphere duplicated the observed bands reasonably well. Thus a relatively small
region could be responsible for the observed absorption and it could easily be confined to the hemisphere not observed by Voyager, which has recently become illuminated by the sun after a long seasonal polar winter night.

On Ariel’s leading hemisphere, we see no convincing evidence for absorption by CO₂ ice. A slight dip does appear near 1.965 μm in our leading hemisphere spectrum. This wavelength is not quite where the CO₂ ice 2ν₁+ν₃ band should be and we see no corresponding features near 2.012 or 2.070 μm where the noise characteristics of our data are much better. We believe the 1.965 μm dip to be spurious, probably a residual feature from imperfect cancellation of telluric absorptions. Using the four model configurations described earlier, we derived approximate upper limits on CO₂ ice for Ariel’s leading hemisphere. For the glaze model, an upper limit of 3 μm of CO₂ ice is consistent with our data. The other models place upper limits on the NH₃:H₂O mixing ratio ranging from 3% for the model having a discrete patch of CO₂ ice to 15% for the model based on linear combinations of CO₂ and H₂O ice optical constants.

Finally, we turn to the question of ammonia. NH₃ has perennially been sought on icy outer solar system surfaces, but has yet to be convincingly identified in spite of possessing several strong, distinctive near-infrared absorption bands, chiefly near 2.0 μm and between 2.20 and 2.25 μm (precise wavelengths and band shapes depend on the hydration state of the NH₃). No evidence is seen in our data for any NH₃ absorption near 2 μm (see Fig. 2) or near 2.2 μm (Fig. 3).

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As we did earlier for CO₂ ice, we used our four model scenarios to set approximate upper limits for NH₃ on Ariel. The maximum admissible global glaze thickness is about 0.1 μm, and upper limits on the mixing ratio of NH₃:H₂O ranged from 0.1% to 2% for our
collection of model scenarios. Likewise for ammonia monohydrate, we derive an upper limit
global glaze thickness of about 1 μm, and upper limit mixing ratios relative to H₂O from
1% to 4%. To construct these models, we used NH₃ ice optical constants from Sill et al.
(1980, unfortunately only available at inadequately low spectral resolution) and ammonia
monohydrate optical constants from Schmitt et al. (1998).

4. Conclusion

We report the discovery of two important spectral differences between the leading
and trailing hemispheres of the Uranian satellite Ariel. First, the H₂O ice absorption
bands are deeper in the leading hemisphere spectrum. This spectral pattern is similar to
leading-trailing asymmetries observed on many Jovian and Saturnian icy satellites. Second,
three absorption bands of CO₂ ice appear in the trailing hemisphere’s spectrum. The
detection of CO₂ ice finally confirms the long-suspected presence of carbon at Ariel’s surface
(e.g., Smith et al. 1986) and also hints at its chemical interaction with the ubiquitous H₂O
ice.

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FIGURE CAPTIONS

Fig. 1.— Spectral observations of Ariel’s leading and trailing hemispheres reveal deeper H\textsubscript{2}O ice I absorption bands on the leading hemisphere (July 17). One spectrum is shifted upward by 0.1 while the other is shifted downward by the same amount.

Fig. 2.— CO\textsubscript{2} ice absorption bands as seen in the spectrum of Triton (arbitrarily scaled), in a simple multiple-scattering model, and on the trailing hemisphere of Ariel (2002 July 16, offset by +0.1), but not on Ariel’s leading hemisphere (2002 July 17, offset by −0.1). The top curve is a telluric transmission spectrum produced by dividing a solar analog star spectrum observed through a high airmass by a spectrum obtained at a lower airmass (arbitrarily scaled). The shapes of the telluric CO\textsubscript{2} vapor absorption bands differ considerably from the CO\textsubscript{2} ice features. Identification of the CO\textsubscript{2} ice transitions is from Quirico and Schmitt (1997).

Fig. 3.— Non-detection of absorption bands of NH\textsubscript{3} or its monohydrate near 2.22 $\mu$m, as shown by Hapke models having 2 to 3 times the upper limit quantities discussed in the text (smooth curves). Each set of spectra was shifted by 0.05, one upward and one downward. $A_1$ is the albedo at a 1° phase angle (e.g., Buie and Grundy 2000). The scaling is based on 0.91 $\mu$m photometry by Karkoschka (1997).
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