Near-Infrared Spectrophotometry of the Satellites and Rings of Uranus

B. T. SOIFER, G. NEUGEBAUER, AND K. MATTHEWS

Palomar Observatory, California Institute of Technology, Pasadena, California 91125

Received November 24, 1980; revised February 10, 1981

New spectrophotometry from 1.5 to 2.5 μm is reported for the Uranian satellites Titania, Oberon, and Umbriel. A spectrum of the rings of Uranus from 2.0 to 2.4 μm is also reported. No evidence is found for frost covering the surface of the ring material, consistent with the low albedo of the rings (P_r = 0.03) previously reported by Nicholson and Jones (1980). The surfaces of the satellites are found to be covered by dirty water frost. Assuming albedos of the frost and gray components covering the Uranian satellites to be the same as the light and dark faces of Iapetus, radii are derived that are roughly twice those inferred from the assumption of a visual albedo of 0.5.

INTRODUCTION

The near-infrared reflection spectra of solar system bodies provide powerful diagnostics of the surface composition of these objects. The unique reflection spectra of water and methane ices have enabled water ice to be identified on the surfaces of the rings and some satellites of Saturn (Pilcher et al., 1970; Fink et al., 1976) and methane ice to be identified on the surface of Pluto (Cruikshank et al., 1976; Lebofsky et al., 1979; Soifer et al., 1980).

Cruikshank (1980) has reported near-infrared spectra of the Uranian satellites Titania and Oberon, from which he has concluded that these satellites are covered by water ice. Nicholson and Jones (1980) have reported spectra of the Uranian disk and total (disk + rings) system from 2.0 to 2.5 μm, in which they find an absorption feature of depth ~20% of the continuum centered at 2.20 μm. They suggest that this feature might be caused either by ammonia frost or OH-bearing silicate minerals in the rings.

We report here spectra that confirm the presence of water frost on Titania and Oberon, and extend this conclusion to the Uranian satellite Umbriel. Spectra of the Uranian disk and rings are also given. These are generally consistent with those of Nicholson and Jones (1980), but are consistent with no absorption feature at 2.2 μm. It is clear that the reflectivity spectrum of the rings is dominated by a featureless continuum, without any distinct features such as those seen in the spectra of the satellites of Uranus.

OBSERVATIONS

The observations reported here were obtained over the period 1978 June to 1980 April on the 5-m Hale telescope at Palomar Mountain with circular variable-filter spectrometers. The instrument and observing techniques are described by Soifer et al. (1981). A journal of the observations is given in Table I.

The satellites of Uranus were observed with 5% spectral resolution over the entire range 1.5–2.5 μm. Observations were obtained at half resolution wavelength spacings. The sky 15° north and south of the object was sampled alternately with the object measurements in order to cancel background emission. The satellites were typically more than 15° from the disk of Uranus; scattered light from the disk of Uranus was therefore negligible. The diaphragms in all cases were 5” in diameter.

The rings of Uranus are difficult to ob-
TABLE I

<table>
<thead>
<tr>
<th>Object</th>
<th>Date observed</th>
<th>Wavelength range (μm)</th>
<th>Δλ/λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oberon</td>
<td>1979 March</td>
<td>1.5–2.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Titania</td>
<td>1980 April</td>
<td>1.5–2.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Umbriel</td>
<td>1980 April</td>
<td>1.5–2.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Rings + Disk</td>
<td>1978 June</td>
<td>2.0–2.4</td>
<td>0.02</td>
</tr>
</tbody>
</table>

serve at most wavelengths because the rings are close to the disk and the scattered light from the disk overwhelms the contribution from the rings. Between 2.0 and 2.4 μm this problem is minimized since the albedo of the disk of Uranus is extremely low due to absorption of incident sunlight by CH₄ in the planet’s atmosphere. Spectra in the range 2.0–2.4 μm were obtained at a wavelength spacing of Δλ = 0.04 μm and with instrumental resolution full width at half maximum of Δλ_{inst} ≈ 0.03 μm.

At the time of the observations, the angular diameter of the disk of Uranus was ~4". The rings, which are nearly circular and which were seen almost face-on, extended from 6 to 8" in diameter. The contribution of the rings was isolated by taking multi-diaphragm observations with 5, 12.5, and 15" diameter diaphragms centered on the disk; the seeing disk was < 2" so the spillage outside the small aperture was less than 20% of the flux from the disk. Since the total flux from the disk and rings is ~3 times that from the disk alone, this is a negligible contribution to the large aperture measurement. The spectrum with a 5" diaphragm is dominated by light reflected from the planetary disk, while the spectra obtained with the larger diaphragms are dominated by the light reflected from the rings. Over the range 2.0–2.4 μm there was no difference to within the uncertainties between the observations measured in the 12.5 and 15" diaphragms.

An inner satellite of Uranus, Ariel, was within the diaphragm sampling the sky south of the planet during the 12.5 and 15" diaphragm observations of Uranus. No account was taken of this in reducing the data. Broadband photometry of Ariel at 2.2 μm suggests that this is at most a 20% effect in the 2-μm flux. If the spectrum of Ariel were similar to that of Titania, this would introduce spectral features of at most 10% into the resultant ring spectrum, less than the noise in the observed spectrum. Miranda was always present in the aperture when observing the rings; however, it was most likely too faint to contribute significant flux.

DATA

Figure 1 shows the spectra of the (disk + rings), the disk, and the difference spectrum (i.e., rings) displayed as relative reflectivities. This was achieved by dividing the observed spectral flux for each object by the solar flux at the wavelength (Arvesen et al., 1969) and arbitrarily normalizing the reflectivity of the (disk + ring) system to unity at 2.28 μm. All of the flux from the disk was assumed to be included by the 5" diaphragm; if this is valid, the difference spectrum represents only the spectrum of the rings. It is seen that the spectrum of the disk is almost featureless; any small spillage of the disk outside the 5" diaphragm thus has little effect on the spectrum of the rings. Figure 1 also shows the laboratory spectra of frosts of methane, ammonia, and water (Smythe 1975).

Figure 2 shows the spectra of the satellites and rings of Uranus reduced to relative reflectivity with each spectrum arbitrarily normalized. For comparison, the observed reflectivities of the bright face of Iapetus (Soifer et al., 1979) and Pluto (Soifer et al., 1980) are shown as well as the reflectivities of H₂O, CH₄, and NH₃ frosts obtained from laboratory measurements (Smythe, 1975).

The spectra reported here for Titania and Oberon agree qualitatively with the data of Cruikshank (1980). Quantitatively, the agreement between the present observations of Titania and those of Cruikshank is
Fig. 1. The relative reflectivities from 2.0 to 2.4 μm of the entire Uranus disk + ring system (an average of the 12.5 and 15° aperture data), the disk (5° observations), and the difference between these observations (labeled rings). The plotted reflectivities are proportional to the observed flux at each wavelength (divided by the solar flux at that wavelength) with a normalization such that the reflectivity of the entire disk + rings system be unity at 2.28 μm. Also shown for comparison are the relative reflectivities of H₂O, CH₄, and NH₃ frosts (Smythe, 1975).

excellent with respect to the wavelength of the peak reflectivity, the relative shape, and the contrast of the reflectivity maxima. In the case of Oberon, the present data show less contrast between the peak reflectivity and minimum reflectivities than that found by Cruikshank, but the two spectra are consistent within the uncertainties.

Within the uncertainties, the reflectivity of the rings of Uranus is flat and featureless from 2.1 to 2.4 μm at a level which is about 60% of the reflectivity at 2.0 μm. The decrease in reflectivity from 2.0 to 2.1 μm appears real, and as noted above is not likely to be simply due to spillage from the planetary disk, although this possibility cannot be ruled out. The apparent structure at wavelength >2.3 μm is due to a high point in the flux from the (disk + rings) at 2.3 μm and a low point in the flux of the disk at the same point. Inspection of Fig. 1 shows that the datum for the large-diaphragm observation is probably too high by ~15%, based on observations less than one resolution element away both longward and shortward of 2.32 μm. Thus, to within the uncertainties, the reflectivity of the rings is essentially constant from 2.1 to 2.4 μm.

Nicholson and Jones (1980) report spectra of the (disk + rings) system and the disk alone from 2.0 to 2.4 μm. The drop in reflectivity between 2.0 and 2.1 μm of 60% in the spectra of the (disk + rings) in Fig. 1 is consistent with a similar drop observed by Nicholson and Jones. There is a dip at 2.20 μm, as reported by Nicholson and Jones, but with the scatter of the data of Fig. 1, this is not a significant feature.

**DISCUSSION**

From the comparison of the frost spectra with the observed spectra of the Uranian ring and disk system, it is clear that such frosts do not contribute a significant fraction (i.e., less than 20%) of the scattered light from the rings. In contrast, the reflection spectra of the satellites of Uranus shown in Fig. 2 all have a reflectivity peak at ~1.8 μm, a significant drop in reflectivity between 1.8 and 2.0 μm, and another reflectivity peak at ~2.2 μm. This behavior is characteristic of the reflectivity of water frost, and shows, in agreement with the observations of Cruikshank (1980), that a substantial fraction of the surfaces of these satellites is covered by water ice. Lebofsky (1975) predicted that ammonia dominated ices would be quite stable at the orbit of Uranus. The observed spectra of the Uranian satellites shows no spectral evidence for such a component.
Fig. 2. The relative reflectivities of the satellites of Uranus, Umbriel, Titania, and Oberon from 1.5 to 2.5 μm. For comparison, the reflectivities of the rings of Uranus, Pluto, and the bright face of Iapetus are shown. Each spectrum is arbitrarily normalized to unity at the peak reflectivity. Also shown for comparison are the 1.5 to 2.5-μm reflectivity spectra of H₂O, CH₄, and NH₃ frosts (Smythe, 1975).
The observations can be used to estimate the radii of the satellites. The contrast in the features of Fig. 2 is much less than that expected from pure water ice of any reasonable particle size (Pollack et al., 1978) and suggests that the surfaces are not "clean" ice surfaces, but, rather, that there is significant contribution to the reflectivities from other material. If the observed scattered light is the sum of a pure ice scattering component and a gray component, the observed spectral distribution of reflectivity can be written

$$R(\lambda)_{\text{obs}} = f_{\text{ice}}R(\lambda)_{\text{ice}} + f_{\text{gray}}R_{\text{gray}},$$

(1)

where $R$ is the reflectivity and $f$ is the fraction of the surface covered by the appropriate material; by assumption, $f_{\text{ice}} + f_{\text{gray}} = 1$. If $R(\lambda)_{\text{ice}}$ and $R_{\text{gray}}$ are assumed to be known, observations of $R(\lambda)_{\text{obs}}$ at two wavelengths give $f_{\text{ice}}$. Equation (1) of course assumes that the reflectivities are additive. It is not clear that this would be true if the ice and gray matter are intimately mixed.

As a first approximation $R(\lambda)_{\text{ice}}$ and $R_{\text{gray}}$ were taken to be those reflectivities derived from the observations of the bright and dark faces of Iapetus (Soifer et al., 1979). The bright face of Iapetus is believed to be purely ice covered, while the dark face shows no evidence for any ice cover. The fractional surface coverings for each satellite derived from the H$_2$O ice spectrum and gray material and the observations at 2.0 and 2.24 \(\mu\)m are given in Table II. The mean albedos, and hence radii of the satellites, can be calculated from the fractional surface coverage given in Table II and the observed fluxes from the satellites. In calculating the satellite radii, it has been assumed that the albedos of the ice and gray material are the same as those determined for Iapetus.

The derived radii of the satellites shown in Table II are significantly larger than the radii derived assuming a visual albedo $P_v = 0.5$ (Cruikshank, 1980). Cruikshank has also noted the possibility of the surfaces of the satellites not being purely ice covered, and has estimated the satellite radii based on a value $P_v = 0.2$. These estimates are shown in Table II and are in reasonable agreement with the radii derived by fitting a gray and ice covering to the observed spectra. There is some evidence which supports the large radii shown in Table II. Dunham (1971) derived a mass $M_{\text{Oberon}} = 0.8 \pm 0.6 \times 10^{-4} M_{\text{Uranus}}$, or $M_{\text{Oberon}} = 5.5 \times 10^{24}$ g, if $M_{\text{Uranus}} = 8.7 \times 10^{26}$ g (Allen 1973). The radius shown in Table II implies a density $\rho_{\text{Oberon}} = 3 \pm 2$ g cm$^{-3}$, rather than the value $\rho = 13 \pm 9$ g cm$^{-3}$ based on the smaller radius given by Cruikshank.

Greenberg (1976) has derived limits on the masses of Ariel and Umbriel based on their effects on the formation of Miranda. This analysis suggests $M_{\text{Umbriel}} \sim 10^{-4.5}$ $M_{\text{Uranus}} \sim 3 \times 10^{24}$ g. The corresponding density derived for Umbriel is $\rho_{\text{Umbriel}} \sim 3$ g cm$^{-3}$. Clearly this value is very uncertain, but is surprisingly close to that derived for Oberon.

If, instead of taking the albedo of the gray material to be that of the dark face of Iapetus [$P(2.2 \mu m) = 0.12$], the albedo is assumed to be that of the rings of Uranus [$P(2.2 \mu m) = 0.03$, Nicholson and Jones, 1980], then as a fraction of the surface area of the satellite, the area covered by gray material increases from 83 to 95% for Oberon, from 75 to 94% for Umbriel, and

### Table II

<table>
<thead>
<tr>
<th>Albedos and Derived Sizes of the Satellites of Uranus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Titania</strong></td>
</tr>
<tr>
<td>$R(2.2 \mu m)/R(2.0 \mu m)$ observed</td>
</tr>
<tr>
<td>$f_{\text{ice}}$</td>
</tr>
<tr>
<td>$P(2.2 \mu m)$</td>
</tr>
<tr>
<td>$R$ (km)</td>
</tr>
<tr>
<td>$\rho$ (g cm$^{-3}$)</td>
</tr>
<tr>
<td>$R$ (km)</td>
</tr>
<tr>
<td>$P_v = 0.5^a$</td>
</tr>
<tr>
<td>$P_v = 0.2^a$</td>
</tr>
</tbody>
</table>

*a* From Cruikshank (1980).
from 55 to 87% for Titania. The resulting decrease in the average surface albedo would imply an approximate doubling of the diameters of the satellites. The visual albedos of the satellites implied by these diameters are 0.04, 0.03, and 0.06 for Oberon, Umbriel, and Titania, respectively. The densities implied decrease by roughly a factor of 8, leading to unrealistically low satellite densities. We therefore conclude that the albedo of the dark face of Iapetus is probably appropriate for the gray component of material in the surfaces of the satellites of Uranus.

SUMMARY

Infrared reflection spectra of the satellites of Uranus, Titania, Oberon, and Umbriel show that these satellites are partially covered with water ice. Radii of the satellites derived from the fractional surface area covered by ice are significantly larger than those based on assumed visual albedos $P_v = 0.5$. The reflectivity of the rings of Uranus is significantly different from the reflectivities of the satellites and shows no evidence in its 2.0 to 2.4-μm spectra for any CH$_4$, NH$_3$, or H$_2$O frost.

ACKNOWLEDGMENTS

We thank Juan Carrasco for assistance with the observations. This research was supported by grants from NASA.

REFERENCES


