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DETECTION OF WATER ICE ON NEREID

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ABSTRACT

We report the detection of the 1.5 and 2.0 μm absorption bands of water ice in the near-infrared reflection spectrum of Neptune's distant irregular satellite Nereid. The spectrum and albedo of Nereid appear intermediate between those of the Uranian satellites Umbriel and Oberon, suggesting a surface composed of a combination of water ice frost and a dark and spectrally neutral material. In contrast, the surface of Nereid appears dissimilar to those of the outer solar system minor planets Chiron, Pholus, and 1997 CU_{26}. The spectrum thus provides support for the hypothesis that Nereid is a regular satellite formed in a circumplanetary environment rather than a captured object.

Subject headings: infrared: solar system — minor planets — planets and satellites: individual (Nereid)

1. INTRODUCTION

The satellite Nereid orbits Neptune in a highly inclined, eccentric, and distant orbit, suggesting that, like other irregular satellites in the solar system, it is possibly a captured body. Goldreich et al. (1989), however, have suggested that Nereid could have formed as a regular satellite of Neptune, but then the capture of Triton and its subsequent orbital circularization could have moved Nereid from an originally regular orbit to its current irregular orbit.

Little evidence exists that would allow discrimination between these scenarios. One suggestive clue is the similarities in albedo and photometric properties between Nereid and the icy Uranian satellites, which could imply that they have related surface compositions (Thomas, Veverka, & Helfenstein 1995) and might have formed in similar circumplanetary environments. If the surface of Nereid is indeed similar in composition to those of the Uranian satellites, infrared spectroscopy should reveal the same water ice absorption bands on Nereid as have been seen on those satellites. Alternatively, the surface composition of the Nereid could be unrelated to those of the Uranian moons, and the photometric similarities could be merely coincidental. Spectroscopy might then be expected to show a composition related to those of distant minor planets like Centaur or Kuiper belt objects. We present here the spectrum of Nereid obtained at the Keck telescope and a comparison to the spectra of the Uranian satellites and other outer solar system bodies.

2. OBSERVATIONS

Near-infrared spectra of Nereid were obtained on 1998 June 16 using the near-infrared camera (Matthews & Soifer 1994) on the Keck telescope. We identified the satellite by its motion in direct *K*-band images and centered it in a 0.″38 wide spectral slit before inserting the 120 line mm^{-1} grism and an *H* through *K* band order sorting filter into the light path, which allowed us to collect a spectrum in first order from 1.4 to 2.5 μm at a resolution of approximately $\lambda/\Delta\lambda = 100$.

We integrated for a total of 3000 s on Nereid at air masses ranging from 1.32 to 1.47. The spectra were obtained by positioning the object in the center of the long slit, integrating for 200 s, and then offsetting the telescope 5″ and 10″ north and then south and obtaining similar exposures. This procedure was performed three times. We then differenced these individual spectra to remove the sky background and extracted a spectrum at each position. Flat-fielding of the spectra was performed by comparison to spectra of a diffusely illuminated dome spot obtained with identical spectrograph settings. To increase the signal-to-noise ratio of the spectra, we binned by 4 pixels in the spectral dimension for a final wavelength sampling of 0.024 μm $pixel^{-1}$.

To correct for telluric absorption, we divided the spectra by the spectrum of a nearby G7 V star (SAO 32071) that was obtained immediately after the target exposures at an air mass of 1.45. We then averaged the individual target spectra and multiplied them by the ratio of the blackbody function of the G7 star divided by that of the Sun to obtain a relative reflectance, which we plot in Figure 1. The spectrum shows two broad absorption features centered at 1.5 and 2.0 μm, which are characteristic of water ice.

3. SPECTRAL COMPARISON

The spectrum of Nereid resembles those of the darker icy satellites of Uranus. To see this resemblance, we compare in Figure 2 the infrared albedo spectra of Oberon and Umbriel (Brown 1983) with Nereid. The infrared albedos are obtained by scaling the measured relative reflectance spectra (normalized by the average of the spectrum from 2.0 to 2.4 μm) by the product of the visual albedo and the $V - K$ color of the satellite (Table 1).

The albedo spectrum of Nereid falls midway between those of Umbriel and Oberon. Brown (1983) showed that the spectra and albedos of Umbriel and Oberon can be modeled as mixtures of water ice frost and a spectrally neutral dark material in either areal or intimate mixtures. The spectrum of Nereid will also be well fit by such models.

In Figure 2 we also show infrared albedo spectra of the Centaur objects Chiron and Pholus (Luu, Jewitt, & Cloutis 1994) and 1997 CU_{26} (Brown & Koresko 1998). Centaur objects are on unstable orbits between the giant planets and are thus related to objects that might become captured satellites of giant planets. Although the data are not always complete between 1.8 and 2.0 μm, each Centaur object so far observed has a distinctive spectrum, and none resembles the spectrum of Nereid. The closest spectral match is to 1997 CU_{26}, which shows water ice absorption features like those of Nereid but

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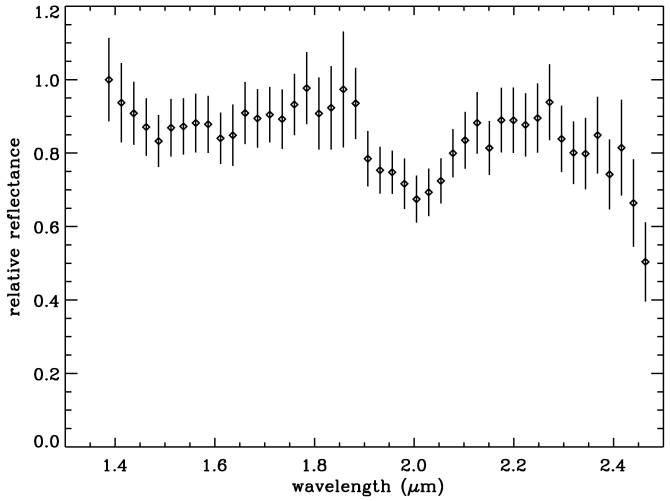

FIG. 1.—Reflectance spectrum of Nereid. The spectrum has been scaled to a value of 1.0 at its highest point. The broad absorptions at 1.5 and 2.0 μm are characteristic of water ice.

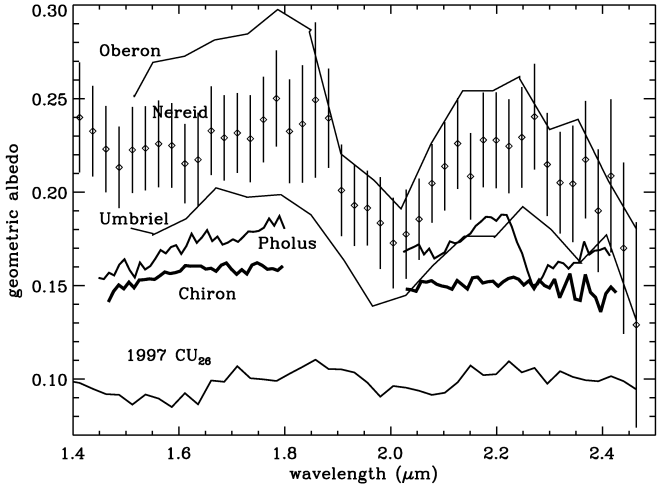

FIG. 2.—Comparison of the geometric albedo spectrum of Nereid with the spectra of the Uranian satellites Oberon and Umbriel (Brown 1983) and the Centaur objects Chiron and Pholus (Luu et al. 1994) and 1997 CU_{26} (Brown & Koresko 1998). The Oberon, Umbriel, and 1997 CU_{26} data are shown as straight lines connecting the individual spectral points. Typical uncertainties are a few percent for Oberon and Umbriel and about 5% in 1997 CU_{26}. Uncertainties in the Pholus and Chiron spectra can be seen from the noise in the spectra.

with weaker absorption features (Brown et al. 1998; Brown & Koresko 1998), a lower albedo, and a much redder $V - K$ color. The comparison with Centaur objects is perhaps suspect because of the possibility that these have been modified by heating as they approach the Sun. Nonetheless, the surface of Nereid does not resemble that of any of the small number of minor planets in the outer solar system that have been studied.

4. CONCLUSION

The infrared reflectance spectrum of Nereid closely resembles that of the Uranian satellites Umbriel and Oberon in both depth of the water ice absorption and absolute value of the reflectance, confirming the suggestion of Thomas et al. (1995) that the surface of Nereid is similar to those of the Uranian satellites. In contrast, none of the minor planets in the outer solar system with both a measured infrared spectrum and albedo appears similar to Nereid, although the number of such objects is still quite small. This situation lends support to the suggestion of Goldreich et al. (1989) that Nereid formed as a regular satellite of Neptune and had its orbit perturbed during the capture of Triton. Unfortunately, while these results are suggestive, without a better understanding of both of the processes affecting surface compositions and the range of variability on both satellites and minor planets in the outer solar system, we are still unable to come to a firm conclusion regarding the origin of Nereid.

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TABLE 1
PROPERTIES OF DISTANT SATELLITES AND MINOR PLANETS

Object	V Albedo	$V - K$	K Albedo	Reference
Oberon	0.29	1.2	0.24	1, 2
Umbriel	0.20	1.2[a]	0.17	1
Nereid	0.18 ± 0.02	1.6[b]	0.21	3
Chiron	0.14^{+6}_{-3}	1.5	0.15	4, 5
Pholus	0.044 ± 0.013	2.9	0.17	6, 7
1997 CU_{26}	0.045 ± 0.01	2.2	0.09	8, 9
Sun	...	1.4	...	10

[a] Assumed to be the same as Oberon.
[b] Measured from our spectral acquisition images.
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