Icarus **139**, 374–378 (1999)
Article ID icar.1999.6109, available online at http://www.idealibrary.com on IDEAL®

NOTE
Water Ice on Nereid

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Received August 13, 1998; revised February 11, 1999

A near-infrared spectrum of Neptune's satellite Nereid was obtained at the Keck Observatory on 1997 May 1. The spectrum shows two absorptions near 1.54 and 2.03 μm and is well matched by a synthetic spectrum of an intimate mix of low-temperature, particulate water ice and dark, blue-colored material. Comparisons of Nereid's spectrum with those of other objects such as the Centaurs 1997 CU_{26} and 5145 Pholus, and Neptune's largest regular satellite Proteus, admit the possibility that Nereid is a primordial satellite of Neptune (and perhaps its only remaining one) rather than a captured object, but more data are needed to rule out one scenario or the other. © 1999 Academic Press

Key Words: **Nereid; surface composition; surfaces, icy; spectroscopy.**

Introduction. G. P. Kuiper (1961) discovered Neptune's satellite Nereid in 1948. Aside from its orbital characteristics and visual brightness, little was known about Nereid until the Voyager 2 flyby of Neptune in 1989, when the spacecraft cameras revealed that the satellite is roughly spherical, with a diameter of 340 ± 50 km. The inner satellite Proteus, discovered by Voyager, is slightly larger, with a diameter of 416 ± 10 km. In the analysis of Voyager data, Smith *et al.* (1989) and Thomas *et al.* (1995) found a geometric albedo of 0.16–0.20 at 0.48-μm wavelength for Nereid, while the albedo of Proteus and the other inner satellites discovered by Voyager is 0.06 (Thomas *et al.* 1995). Thomas *et al.* (1995) found that Nereid has a slightly bluish color, while Proteus has a slightly reddish color in the Voyager wavelength range of 0.4–0.55 μm. Ground-based photometry of Nereid by Buratti *et al.* (1997) yielded a slightly lower geometric albedo of 0.15–0.18 over the range 0.4–0.7 μm. Buratti *et al.* (1997) note that Nereid is similar in color and albedo to Uranus' satellite Umbriel.

Nereid's orbit is inclined to Neptune's equator by 27.6° and has an eccentricity of 0.75 (Burns 1986). The high eccentricity and inclination of Nereid's orbit have given rise to speculation that it may be a captured object, but Goldreich *et al.* (1989) have argued that Nereid could be one of Neptune's primordial satellites whose orbit was perturbed into its present state during the circularization of Triton's orbit after its hypothetical capture by Neptune.

In the Goldreich *et al.* (1989) scenario, Triton was captured into a highly elliptical orbit about Neptune by collision with one of Neptune's primordial satellites. After the capture, Triton's orbit was circularized by dissipation of its orbital energy through tides raised on Triton by Neptune. Goldreich *et al.* hypothesize Triton could have crossed the orbit of the primordial Nereid (which was assumed to be one of Neptune's regular satellites by Goldreich *et al.*) on the order of 10^8 times during this period (less than about 10^9 years), eventually perturbing Nereid into the orbit we see today.

If Nereid is indeed a captured object, it could show compositional similarities to bodies that are in heliocentric orbit near Neptune such as objects near the inner edge of the Kuiper belt or objects that may have passed through Neptune's neighborhood such as Centaurs. Therefore, comparisons of the surface and bulk composition of Nereid to the compositions of objects such as Centaurs and Kuiper belt objects (KBOs) may shed light on Nereid's origin. To help address such a question we have obtained infrared spectroscopic observations of Nereid.

Observations and model fitting. We obtained a near-infrared spectrum of Nereid at the Keck Observatory on 1997 May 1, using the Near Infrared Camera (NIRC). The spectral measurements were made using the gr120 grism of the NIRC over the wavelength region 1.40–2.40 μm with a sampling interval of 0.00607 μm. A pixel projected on the sky in this configuration is 0.15 arcsec, and a slit width of 4.5 pixels (0.7 arcsec) was used. Atmospheric seeing was about 0.4 arcsec (full width at half maximum) at 2.16 μm. Nereid was identified in direct images (using a filter with bandpass 1.99–2.32 μm) by its motion and its predicted position on the sky relative to Neptune.

Spectra of 1800 s exposure (20 separate exposures of 90 s co-added) were measured with each exposure offset along the grism slit by 4 arcsec alternately north then south. Corresponding pairs of images were differenced, allowing a first-order subtraction of the sky. Residual sky background was removed by least-squares fitting column by column (perpendicular to the dispersion) in the sky-subtracted images. Our fully reduced spectrum of Nereid encompasses 3600 s of integration. Correction for telluric extinction and the solar color was accomplished by measuring spectra of the C-type asteroid 238 Hypatia obtained on the same night and over the same airmass range. C-type asteroids typically have flat and featureless spectra in the wavelength range of the observations presented here, but sometimes their reflectance is slightly red, sloping upward toward longer wavelengths (e.g., Barucci *et al.* 1994).

Figure 1 shows our scaled, full-resolution spectrum of Nereid, accompanied by the same spectrum convolved with a Gaussian of 10 spectral channels in width to increase the signal-to-noise ratio (SNR). We used a direct, discrete, numerical-integration convolution (not a Fourier convolution) to model data

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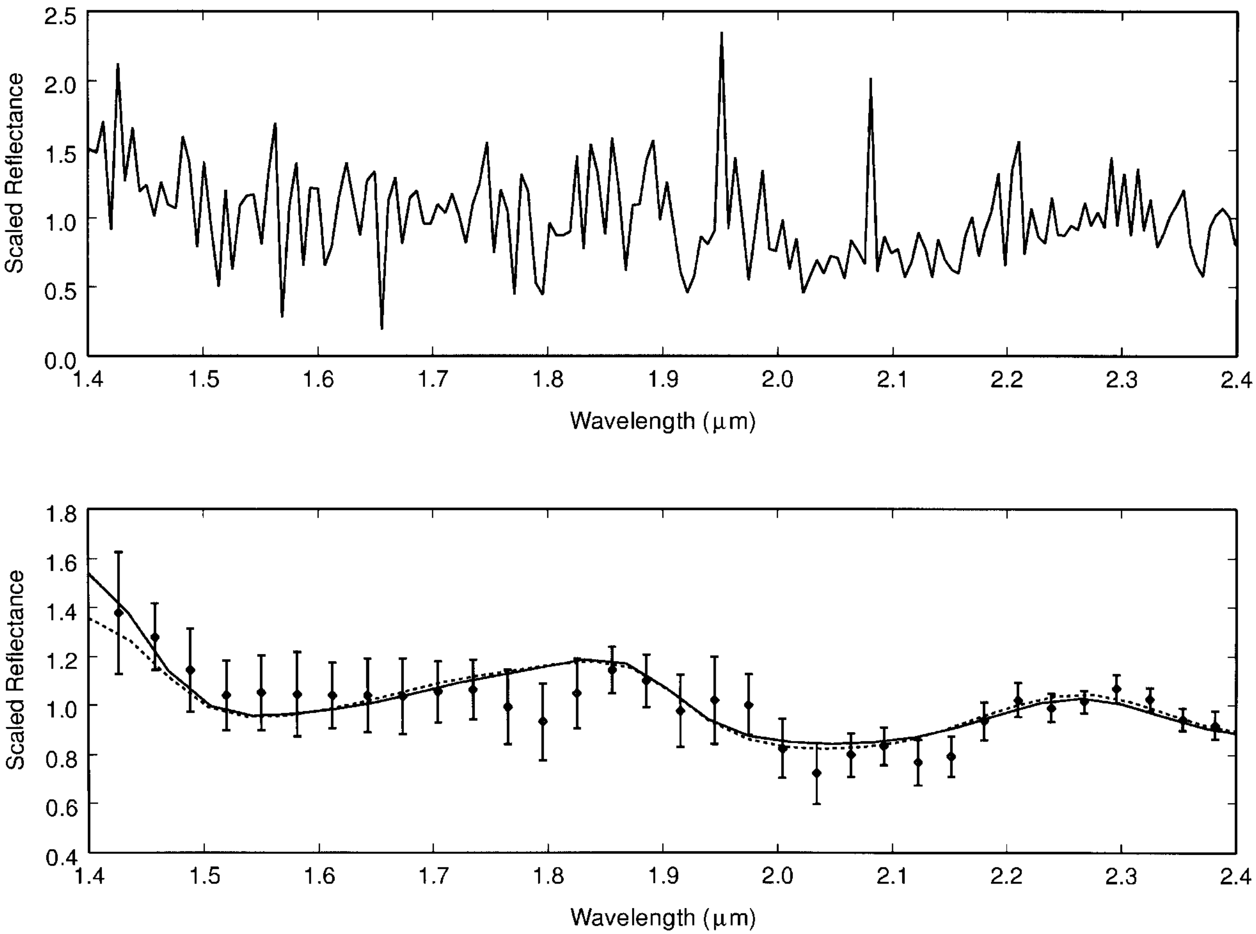

FIG. 1. High- and low-resolution spectra of Nereid. The upper spectrum represents 3600 s of integration and is presented at full resolution. The spectrum has been scaled such that the mean reflectance over the passband equals 1. The lower spectrum has been convolved with a Gaussian whose full width at half maximum is equal to 10 fundamental resolution elements of the raw spectrum. The error bars are 1 sigma of the mean estimated from the repeatability of the high-resolution measurements and propagated through the discrete convolution. Plotted with the data are model spectra at the same resolution and sampling interval. The dotted line is a model spectrum of an intimate mixture of water ice and a dark, spectrally featureless, and blue-colored material. The solid line is an areal mixture of water ice and our simulated blue, dark material. The absolute reflectance of the areal mix model spectrum is about 15% at 1 μm, matching roughly the visual geometric albedo of Nereid determined from Voyager data.

obtained at intrinsically lower spectral resolution. In contrast to binning data, which is equivalent to convolving with a square wave (with the attendant Fourier spectral aliasing), the bandpass of most grating and grism spectrometers is very nearly Gaussian. Thus, the result of our procedure is a better approximation to spectral data obtained at lower resolution than would be achieved by binning.

We have fit a model spectrum of an intimate mix of particulate water ice and a dark, spectrally featureless, slightly blue-colored material to the low-resolution spectrum. The model was computed with Hapke theory (Hapke 1993), using optical constants of H_2O ice taken from Warren (1984) and shifted in wavelength to agree with the results of Toon *et al.* (1994). The complex refractive indices (n, k) in Warren were deemed to be more precise in the 1.4- to 2.4-μm wavelength region than those in Toon *et al.*, but the central wavelengths of the absorption bands in the Toon *et al.* data correspond more closely with those of H_2O ice at the roughly 60 K (average) surface temperature of Nereid. A low-albedo material was included in the scattering calculations. This material has a slightly blue color in order to reproduce the slope in the observed spectrum; the optical constants of the low-albedo blue material were derived by assuming a real index (n) of 1.4 at wavelength 1.0 μm, and assuming a Lambert absorption coefficient that decreases linearly toward longer wavelengths. These quantities were processed through a subtractive Kramers–Kronig algorithm giving the real indices of refraction corresponding to the defined imaginary indices and the real index in the visual spectral region. The calculated reflectance for 10-μm grains gives a roughly linear decrease in reflectance from about 0.075 at 1.0 μm to about 0.060 at 2.5 μm. While solid CO_2 and some other molecules have absorption bands at or near 2 μm, the shape of their spectra in other parts of the wavelength region covered here diverge from the Nereid spectrum. We cannot eliminate the possibility that a small amount of CO_2, or some other molecules, is also present on Nereid, but a critical test for other components requires spectra of higher resolution and signal precision than is presently possible.

The primary effects of the dark material in this model are to lower the average spectral reflectance, make the continuum reflectance bluer, and reduce the contrast in the strong absorptions at 1.54 and 2.03 μm. The model spectrum is a good match to that of Nereid and demonstrates that Nereid's surface is at least partially composed of H_2O ice, intimately mixed with a blue-colored material that is spectrally featureless in this wavelength region. It is possible that some of the blue slope to the data is introduced by a slightly red reflectance of the comparison asteroid 238 Hypatia. We do not have an independently measured spectrum of this asteroid.

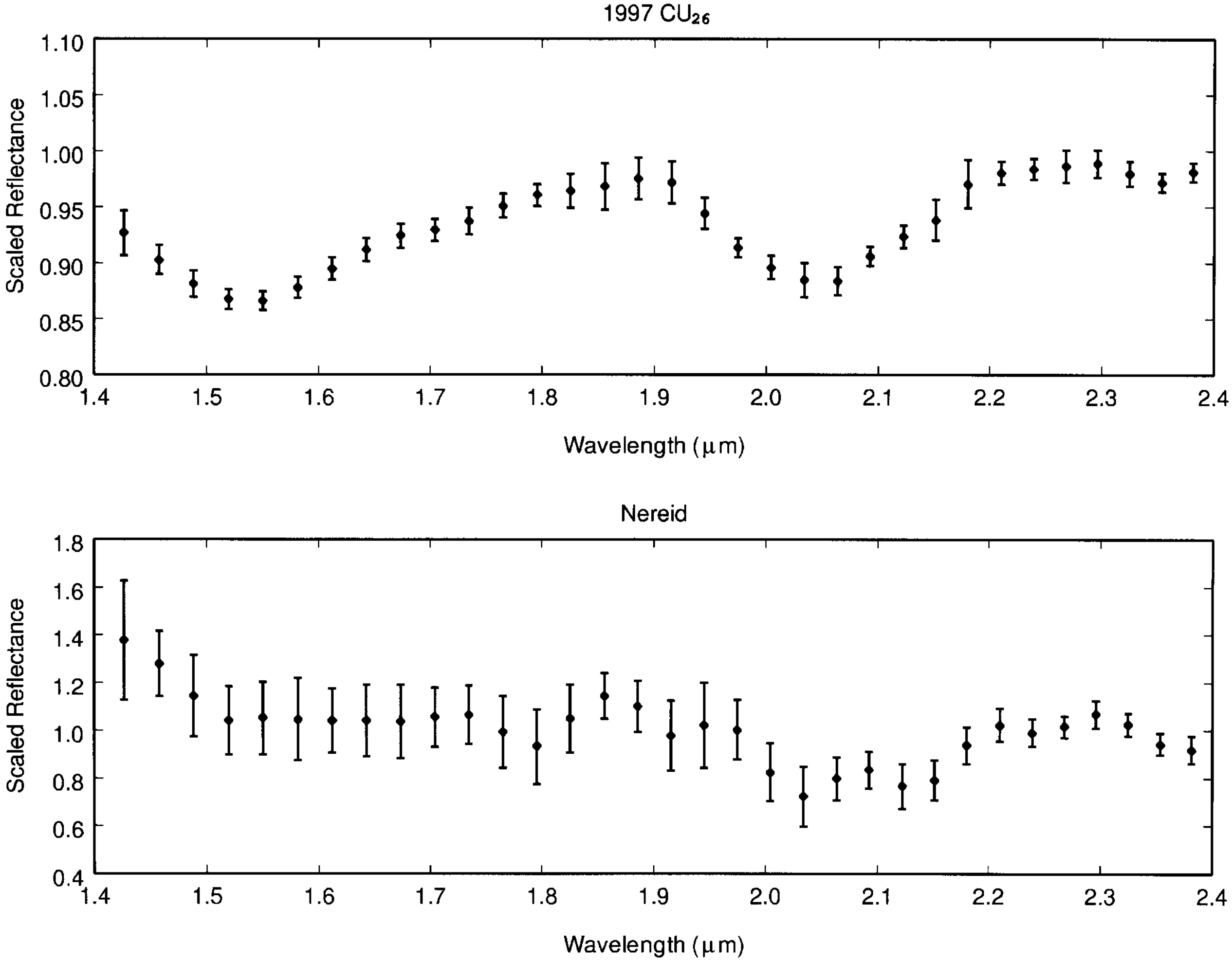

FIG. 2. The spectra of 1997 CU_{26} and Nereid. The spectrum of 1997 CU_{26} is taken from Brown *et al.* (1997).

If we assume that the dark material and the H_2O ice on Nereid exist in pure, spatially isolated patches, we can also construct a model that matches Nereid's near-infrared spectrum (see Fig. 1). Either intimate-mix or areal-mix models can be made to match the geometric albedo of Nereid extrapolated into the visual spectral region. Thus, whether Nereid's surface components are mixed primarily at the grain-to-grain level (intimate mixture) or mainly in segregated, isolated patches (areal mixture) cannot be uniquely determined from the existing spectral data. Nevertheless, the best Voyager image of Nereid shows a "patchy" surface (Smith *et al.* 1989), suggesting that Nereid has albedo contrast, at least in the visual region of the spectrum where Voyager's cameras are sensitive. The patchy surface supports a surface spectral model which has some albedo contrast.

Discussion. It may be instructive to compare Nereid's surface composition to that of other objects in the outer Solar System such as the Centaurs and KBOs. The orbits of the Centaurs (of which 7 are known) are dynamically unstable on time scales of about 10^6 to 10^7 years (e.g., Gladman and Duncan 1990, Holman and Wisdom 1993, Dones *et al.* 1996). Thus, their existence implies a source of new bodies to replenish those lost by collisions or catastrophic gravitational encounters with the jovian planets. The presumed source of the Centaurs is the Kuiper belt (e.g., Gladman and Duncan 1990).

Infrared spectra of three Centaurs have been published: 5145 Pholus (Luu *et al.* 1994, Cruikshank *et al.* 1998), 2060 Chiron (Luu *et al.* 1994), and 1997 CU_{26} (Davies *et al.* 1993, Brown *et al.* 1998, Brown and Koresko 1998). Pholus shows a complex spectrum which has been modeled with a mixture of complex refractory organics, olivine, H_2O ice, CH_3OH ice, and amorphous carbon (Cruikshank *et al.* 1998). Chiron's spectrum is virtually devoid of color and detectable absorption features in existing data (Luu *et al.* 1994). Neither of these two objects shows a close spectral resemblance to Nereid, although Pholus does seem to have water ice and dark material on its surface. The closest spectral analog for Nereid among the Centaurs is 1997 CU_{26} (Brown *et al.* 1998) (Fig. 2). Both spectra show water-ice absorptions, but the absorption bands of Nereid are slightly stronger than those of 1997 CU_{26}, perhaps reflecting Nereid's higher albedo and a greater amount of H_2O ice on its surface (Jewitt and Kalas (1998) derive an albedo 0.045 ± 0.010 for 1997 CU_{26}). In both spectra the absorptions are much weaker and broader than those of pure, fine-grained (a few tens of micrometers in size) water ice, implying water-ice grain sizes in the several hundred micrometer range and tens of percent by weight of dark material on both objects (Brown *et al.* 1998). An obvious difference between the two objects is in the slopes of their continuum reflectance. 1997 CU_{26} has a neutral to slightly reddish continuum reflectance while that of Nereid is somewhat blue.

Because water ice is widespread (perhaps ubiquitous) in the outer Solar System (Brown and Cruikshank 1997), the presence of water ice on Nereid is of little help in answering the question of where Nereid was formed. Instead we look to the dark material on Nereid to provide possible constraints. Pure, particulate water ice, almost regardless of its grain size, has a strongly blue continuum slope in the 1.4- to 2.4-μm region, due mainly to the increasing strength of its combination and overtone bands as the wavelength increases. If water ice is mixed with colored, dark material, the continuum reflectance of the mixture increasingly approaches that of the dark material as its abundance is increased (Clark 1981, Clark and Lucey 1984, Clark and Roush 1984). Thus, the continuum reflectance of a water-ice–dark-material mixture can have a wide range of slopes, depending upon the coloring agent and its concentration.

The above discussion implies that if a mixture of water ice and colored, but otherwise dark and spectrally featureless, material has a red continuum in the 1.4- to 2.4-μm region, it must result from the red color of the dark material. If the continuum reflectance is blue, it can result from the presence of a neutral- or blue-colored material, depending upon the abundance of the coloring agent and the average size of the water-ice grains. Thus, the difference in continuum reflectance between Nereid and 1997 CU_{26} must be due to a difference in the color and probably the chemical composition of the dark material. In principle, the difference in the dark components on Nereid and 1997 CU_{26} admits the possibility that the two objects formed from different reservoirs of material. This view is supported by the difference in visual color between Nereid and one of Neptune's inner satellites Proteus, and the high theoretical probability that Neptune's primordial satellites were destroyed and reaccreted several times during the early history of the Neptune system, possibly incorporating large amounts of material from heliocentric impactors (Smith *et al.* 1989, Banfield and Murray 1992).

From the standpoint of dynamics it is quite compelling that the Kuiper belt is the source of the Centaurs (e.g., Holman and Wisdom 1993), thus it might be expected that these groups of objects would show some recognizable, compositional patterns. While the sample of observed objects is still quite small, some apparent patterns show in the existing data. The KBO 1996 TL_{66} (Luu and Jewitt 1998, Brown *et al.* 1999, in preparation) shows a relatively flat spectrum which is almost featureless, and resembles that of the Centaur Chiron. The KBO 1993 SC (Brown *et al.* 1997) shows a number of near-infrared spectral features and has no direct spectral analog among the Centaurs, except that it may have light hydrocarbons on its surface like Pholus. The closest compositional analogs to Nereid presently known are the Centaur 1997 CU_{26} and the KBO 1996 TO_{66}, both of which have clear evidence of H_2O ice on their surfaces (Brown *et al.* 1998, Brown and Koresko 1998, Brown *et al.* 1999). A partial explanation for the differences may be that when objects leave the Kuiper belt and more closely approach the Sun, their surfaces are altered, both chemically and physically. For example, if ices such as methane or methanol are irradiated with photons or charged particles, chemical bonds are broken and the material proceeds to molecules with increasingly higher carbon abundances (Sagan *et al.* 1984, Andronico *et al.* 1987, Thompson *et al.* 1987, Strazzulla *et al.* 1997). If the photolytic and/or radiolytic dose is large enough, in time the color of a high-albedo surface initially composed of light hydrocarbon and water ices can proceed from bluish to very red and eventually back to neutral with a very low albedo (3–5%).

Thus, the combined photolysis, radiolysis, and thermal escape of volatile material could lead to substantial devolatilization and carbonization of an originally volatile-rich surface (where water ice at the temperatures of interest here is considered nonvolatile). In some cases, enough dark material may be left behind that absorption bands due to residual water ice in the surface layers would be completely masked. Thus, one possible compositional connection between KBOs and Centaurs could lie in faster and more complete photochemical alteration and devolatilization of the Centaurs' near-surface layers (because they are closer to the Sun), where a possible end state is a surface having a flat, featureless spectrum similar to that of amorphous carbon (see also Cruikshank *et al.* 1998). Crucial parameters in this scenario are the initial inventory of primordial dark material and light hydrocarbons. If the inventories are too low, the final albedo of the surface would be relatively high (where 3–5% would be considered low) and the water-ice absorption bands in the 1- to 2.5-μm spectral region would never be completely masked.

If the above scenario applies, and if Nereid had been a Centaur or a KBO before being captured by Neptune, then one might suspect that Nereid's near surface layers would be mostly devolatilized, resulting in a flat to slightly red spectrum with weak to nonexistent H_2O bands. That its spectrum shows weak water-ice absorptions and bluish, dark material, while Proteus, the Centaurs Pholus, Chiron, and 1997 CU_{26}, and the KBOs 1996 TL_{66} and 1993 SC have spectra that suggest that their dark material is neutral to red, admits the possibility that Nereid formed from a different reservoir of material. Nevertheless, that we do not fully understand the long-term effects of photolysis, radiolysis, and surface heating of objects in the outer Solar System councils caution when attempting to use surface composition to constrain origin scenarios. Thus, the strongest conclusion that can be drawn from the this work is that Nereid's surface contains water ice, a fact corroborated in an independent investigation by Brown *et al.* (1998).

ACKNOWLEDGMENTS

The W. M. Keck Observatory is operated as a scientific partnership between the California Institute of Technology and the University of California. It was made possible by the generous financial support of the W. M. Keck Foundation. The authors are happy to acknowledge the assistance of Rachel Mastrapa at the telescope, and the financial support of the National Aeronautics and Space Administration through the grants and contracts that support the authors' work.

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