Water Ice in 2060 Chiron and its Implications for Centaurs and Kuiper Belt Objects

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ABSTRACT

We report the detection of water ice in the Centaur 2060 Chiron, based on near-infrared spectra (1.0 - 2.5 μm) taken with the 3.8-meter United Kingdom Infrared Telescope (UKIRT) and the 10-meter Keck Telescope. The appearance of this ice is correlated with the recent decline in Chiron's cometary activity: the decrease in the coma cross-section allows previously hidden solid-state surface features to be seen. We predict that water ice is ubiquitous among Centaurs and Kuiper Belt objects, but its surface coverage varies from object to object, and thus determines its detectability and the occurrence of cometary activity.

Subject headings: comets – Kuiper Belt – solar system: formation

1. Introduction

The Centaurs are a set of solar system objects whose orbits are confined between those of Jupiter and Neptune. Their planet-crossing orbits imply a short dynamical lifetime ($10^6 - 10^7$ yr). The current belief is that Centaurs are objects scattered from the Kuiper Belt that may eventually end up in the inner solar system as short-period comets. The first discovered and brightest known Centaur, 2060 Chiron, is relatively well studied. The object is firmly established as a comet, with a weak but persistent coma. It is well documented that Chiron possesses neutral colors (e.g., Hartmann et al. 1990, Luu and Jewitt 1990), and a low albedo of $0.14^{+0.06}_{-0.03}$ (Campins et al. 1994). (It must be noted that most of these measurements were made when Chiron clearly exhibited a coma so that the measurements are likely to have been contaminated by dust scattering from the coma. The albedo, in particular, should be viewed as an upper limit). Chiron has a rotation period of $\sim$ 6 hr (e.g., Bus et al. 1989) and a photometric amplitude that is modulated by the cometary activity level (Luu and Jewitt 1990, Marcialis and Buratti 1993, Lazzaro et al. 1997). Published optical and near-IR spectra of Chiron show a nearly solar spectrum, varying from slightly blue to completely neutral (Hartmann et al. 1990, Luu 1993, Luu et al. 1994, Davies et al. 1998), and devoid of specific mineralogical features.

As a group, the Centaurs display remarkable spectral diversity (e.g., Luu and Jewitt 1996). The Centaur 5145 Pholus is among the reddest bodies in the solar system (Mueller et al. 1992, Fink et al. 1992), and shows absorption features at 2.00 and 2.25 μm (see, e.g., Davies et al. 1993a, Luu et al. 1994). Cruikshank et al. (1998) interpreted the 2.0 μm feature as due to water ice, and the 2.27 μm due to methanol. They derived a best fit to the spectrum which consisted of carbon black and an olivine-tholin-water-methanol mixture. Pholus's extreme red color and low albedo (0.044 ± 0.013, Davies et al. 1993b) strongly suggest that long-term irradiation of carbon- and nitrogen-bearing ices has resulted in an organic-rich, dark "irradiation mantle" (e.g., Johnson et al. 1987). The spectral differences between Chiron and Pholus have been attributed to the presence of cometary activity in Chiron and the lack thereof in Pholus (Luu 1993, Luu et al. 1994). A continuous rain of sub-orbital cometary debris falling onto the surface of Chiron may have buried a more primordial irradiation mantle with unirradiated matter ejected from the interior. In this paper we show further evidence supporting this hypothesis, and that scattering effects by coma dust particles also eliminate spectral features seen in solid surface reflection.

2. Observations

(a) Keck observations. The Keck near-infrared observations were made on UT 1999 April 03, at the $f/25$ Cassegrain focus of the Keck I telescope, using the NIRC camera (Matthews and Soifer 1994). The NIRC detector is a 256 x 256 pixel InSb array that can be switched from direct imaging to slit spectroscopy. In imaging mode the pixel scale is

0.15 arcsec per pixel (38" x 38" field of view), and in spectroscopy mode the resolution is $\lambda/\Delta\lambda \approx 100$. We used a 0.68" $\times$ 38" north-south slit for all spectral observations. Uneven illumination of the slit and pixel-to-pixel variations were corrected with spectral flat fields obtained from a diffusely illuminated spot inside the dome.

Since the target was not visible during spectral observations, Chiron's position was confirmed by centering it at the location of the slit and taking an image. The slit, grism, and blocking filter were then inserted in the beam for the spectroscopic observation. Spectra were made in pairs dithered along the slit by 13". We obtained spectra in two different grating positions, covering the JH wavelength region (1.00 - 1.50 μm) and the HK region (1.4 - 2.5 μm). Non-sidereal tracking at Keck showed a slight drift with time, so we recentered Chiron in the slit every 15-20 minutes.

(b) UKIRT observations. The UKIRT observations were made on UT 1996 Feb 7 and 8 with the CGS4 infrared spectrometer mounted at the Cassegrain focus. The detector was a 256 $\times$ 256 pixel InSb array, with a 1.2" per pixel scale in the spatial direction. An optical TV camera fed by a dichroic beam splitter gave us slit viewing capability and thus we were able to guide on the target during all observations. The conditions were photometric and the image quality was $\sim$ 1" Full Width at Half Max (FWHM), so we used a 1.2" $\times$ 80" slit aligned North-South on the sky at all times. A 75 line per mm grating was used in first order for all observations, yielding a dispersion of 0.0026 μm/pixel in the H and K band ($\lambda/\Delta\lambda \approx 850$). However, the detector was dithered by 1/2 pixel during each observation, so the spectra were oversampled by a factor of 2. The effective spectral coverage in the H band was 1.4 – 2.0 μm and in the K band 1.9 – 2.4 μm. Sky background removal was achieved by nodding the telescope 30" (23 pixels) along the slit. Dark frames and calibration spectra of flat fields and comparison lamps (Ar) were also taken every night.

Both the Keck and UKIRT observations were calibrated using stars on the UKIRT

Faint Standards list (Casali and Hawarden 1992). At both telescopes, we took care to observe the standard stars at airmasses similar to those of Chiron (airmass difference $\leq$ 0.10), to ensure proper cancellation of sky lines.

The separate reflectance spectra from each night of observation are shown in Fig. 1.

3. Discussion

3.1. The spectra

The Chiron spectra (Fig. 1) show that: (a) Chiron is nearly neutral in the 1.0 – 2.5 μm region; (b) there is a subtle but definite absorption feature at 2 μm ($\sim$ 0.35 μm wide, $\sim$ 10% deep) in spectra from 1996 and 1999, and a marginal absorption feature near 1.5 μm in the 1999 spectrum; and (c) the spectral slope and the strength of the 2 μm feature change with time.

Reflectivity gradients in the JHK region span the range S' = -2 %/1000 Å to S' = 1%/1000 Å (Table 2). In Fig. 2 we compare Chiron spectra from 1993 (from Luu et al. 1994) with the present observations. The flat and featureless 2 μm spectrum from 1993 stands in sharp contrast with the later spectra. The presence of the 2 μm feature in different spectra taken with different telescopes, instruments, and spectral resolutions provides convincing evidence that it is real.

The 2 μm and 1.5 μm features are clear signatures of water ice, and the shallowness of the features (compared to that of pure water ice) indicates that this ice is mixed with dark impurities (see Clark and Lucey 1984). We note that the Chiron spectra are very similar to spectra of minerals and water ice (compare the spectra in Fig. 2 with Fig. 14 and 15 of Clark 1981, respectively). In Fig. 3 we show that the Keck Chiron spectrum is well fitted by a model consisting of a linear superposition of a water ice spectrum and an olivine spectrum. The olivine spectrum is needed to provide the required continuum slope, and at the very small grain size used, the spectrum of olivine is essentially featureless. The water ice spectrum was calculated based on the Hapke theory for diffuse reflectance (Hapke 1993) and used a grain diameter of 1 μm. A description can be found in Roush (1994). However, we caution that the model is non-unique, and due to the many free parameters in the model (e.g., grain albedo, porosity, roughness), the 1μm grain size should not be taken literally. Similarly, olivine could also be replaced in the fit by other moderately red, featureless absorbers.

The 2 μm feature in Chiron is clearly time-variable: it was not apparent in 1993 but changed to a depth of 8 - 10% in 1996 and 1999. Chiron's lightcurve variations can be explained by the dilution of the lightcurve by an optically thin coma (Luu and Jewitt 1990). Based on this model, we estimate that the 1993 coma cross-section was $\sim$ 1.5 times larger than in 1996 or now. The likeliest explanation for the time-variability of the 2μm feature is the degree of cometary activity in Chiron. In 1993, Chiron's activity level was high (Luu and Jewitt 1993, Lazzaro et al. 1997), resulting in a featureless spectrum dominated by scattering from the coma. By 1996, when the UKIRT observations were made, Chiron's total brightness had dropped by $\sim$ 1 mag to a minimum level (comparable to that of 1983–1985, Lazzaro et al. 1997), leaving spectral contamination by dust at a minimum.

3.2. Implications of water ice on Chiron

3.2.1. Cometary activity in Centaurs

Considering (1) Chiron's time-variable spectrum, (2) the presence of surface water ice, and (3) Chiron's persistent cometary activity, we conclude that Chiron's surface coverage is *not* dominated by an irradiated mantle but more probably by a layer of cometary debris.

Occultation observations suggest that sublimation by supervolatiles (e.g., CO, N_2) on Chiron occurs in a few localized icy areas (Bus et al. 1996). Dust grains ejected at speeds < 100 m s^{-1} (the escape velocity) will reimpact the surface, building a refractory layer which tends to quench sublimation. Nevertheless, the outgassing is still sustained by the sporadic exposure of fresh ice on the surface. Sublimation experiments with cometary analogs illustrate this phenomenon: outgassing produces a dust layer, but fresh icy material can still be periodically exposed by avalanches and new vents created by impacts from large dust particles (Grün et al. 1993). If, in keeping with a Kuiper Belt origin, Chiron once possessed an irradiation mantle, we suspect that it has been either blown off by sublimation or buried under a dust layer thick enough to mask its features. If so, the present low albedo of Chiron would be due to cometary dust particles rather than irradiated material.

In contrast, the lack of cometary activity in the Centaur Pholus is consistent with an encompassing surface coverage by the irradiation mantle – witness the extreme red color and absorption features associated with hydrocarbon materials. Although water ice may exist locally on the surface (Cruikshank et al. 1998), Pholus's spectral properties are still dominated by the organic irradiated crust. If this hypothesis is correct, cometary activity should be uncommon among Centaurs with very red colors (irradiated material), and more common among those with neutral (ice) colors. As the observational sample of Centaurs grows, this is a simple prediction that can be directly tested. However, it remains unclear why cometary activity was activated on Chiron and not on Pholus, even though the two Centaurs are at similar heliocentric distances. One possibility is that Pholus was recently expelled from the Kuiper Belt and has not yet been heated internally to a degree sufficient to blow off the irradiation mantle, but this hypothesis cannot be easily tested, given the chaotic nature of the orbits of Centaurs.

3.2.2. Centaur and Kuiper Belt surfaces

We summarize the spectral properties of Centaurs and KBOs in Table 3. Thus far, water ice has been reported in 3 Centaurs (Chiron, Pholus, 1997 CU_{26}) and 1 KBO (1996 TO_{66}). The existing data are too sparse to establish whether a correlation exists between color and the abundance of water ice among Centaurs and KBOs. However, water ice is present in all three Centaurs for which near-IR spectra are available, and in 1 out of 3 studied KBOs. The preponderance of water ice among Centaurs makes us suspect that that the "low" rate of detection of water ice in KBOs has more to do with the faintness of the targets and the resulting low-quality spectra than with the intrinsic water contents in KBOs. Considering the existing data and the high cosmochemical abundance of water ice, we predict that water ice is ubiquitous among *all* objects that originated in the Kuiper Belt, although the amount might vary from one object to another and thus determines the possibility for cometary activity in these bodies.

In short, it would be a good idea to re-observe those KBOs which show no apparent water ice feature (1993 SC and 1996 TL_{66}) at higher signal-to-noise ratios. Water ice might be present after all.

4. Summary

1. The near-infrared reflectance spectrum of Chiron is time-variable: in 1996 and 1999 it shows an absorption feature at 2 μm due to water ice. Another absorption feature due to water ice at 1.5 μm is also marginally detected in 1999. The features were not present in spectra taken in 1993.

2. Chiron's time-variable spectrum is consistent with variable dilution by the coma. During periods of low-level outgassing, surface features are revealed.

3. Chiron's nearly neutral spectrum suggests the surface dominance of a dust layer created from cometary debris, consisting of unirradiated dust particles from the interior. Chiron's original irradiation mantle has either been blown off or buried under this layer.

4. Chiron is the third Centaur in which water ice has been detected. This trend suggests that water ice is common on the surface of Centaurs. We predict that water ice is ubiquitous in *all* objects originating in the Kuiper Belt. The surface coverage of this water ice determines its detectability.

Note - As we finished the preparation of this manuscript, we received a preprint by Foster et al. (1999) in which water ice is independently identified in spectra from 1998. Foster et al. also report an unidentified absorption feature at 2.15 μm that is not confirmed in our spectra.

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FIGURE CAPTIONS

Figure 1. Infrared reflectance spectrum of 2060 Chiron, normalized at 2.2 μm. The date of each spectrum is indicated. The top panel shows the original spectra, while in the bottom panel the 1996 spectra have been smoothed by 3 pixels (the 1999 spectrum remains unsmoothed). There is a clear absorption feature at 2 μm in all three spectra, and a very weak absorption feature at 1.5 μm in the 1999 spectra.

Figure 2. Infrared reflectance spectrum of Chiron from 1993 (from Luu et al. 1994) compared with the 1996 and 1999 spectra. There was no apparent spectral feature in the 1993 spectra.

Figure 3. Chiron's 1996 spectra fitted with a model consisting of a linear superposition of water ice and olivine spectra.

Table 1. Observational Parameters of Spectra

UT Date	Instrument	Wavelength [μm]	Slit [arcsec]	$\lambda/\Delta\lambda$	Int[a] [sec]	R[b] [AU]	Δ[c] [AU]	α[d] [deg]
UKIRT								
1996 Feb 7	CGS4 K	1.3 - 2.0	1.2"$\times$ 80"	$\sim$ 850	1080	8.45	7.86	5.6
1996 Feb 8	CGS4 H	1.3 - 2.0	1.2"$\times$ 80"	$\sim$ 850	400	8.45	7.85	5.5
1996 Feb 8	CGS4 K	1.9 - 2.4	1.2"$\times$ 80"	$\sim$ 850	1520	8.45	7.85	5.5
Keck I								
1999 Apr 3	NIRC JH	1.00 - 1.55	0.68" $\times$ 38"	$\sim$ 100	600	9.39	8.72	4.7
1999 Apr 3	NIRC HK	1.35 - 2.50	0.68" $\times$ 38"	$\sim$ 100	600	9.39	8.72	4.7

[a]Accumulated integration time on Chiron

[b]Heliocentric distance

[c]Geocentric distance

[d]Phase angle

Table 2. Reflectivity Gradients of Chiron Spectra

UT Date	Instrument	Wavelength Range [μm]	S' [%/1000Å]
1996 Feb 7	CGS4 K	2.0 – 2.4	0.7 ± 0.2
1996 Feb 8	CGS4 H	1.4 – 2.0	-0.3 ± 0.2
1996 Feb 8	CGS4 K	2.0 – 2.4	-2.1 ± 0.3
1999 Apr 3	NIRC JH	1.0 – 1.5	0.9 ± 0.2
1999 Apr 3	NIRC HK	1.5 – 2.5	-0.8 ± 0.1

Table 3. Spectral Properties of Centaurs and Kuiper Belt Objects

Object	Type	p_V[a] [%]	V-J	$D_{2\mu m}$[b] [%]
2060 Chiron	Centaur	$\leq 0.14^{+0.06}_{-0.03}$	1.24 ± 0.02	10
		(1)	(2)	This work
5145 Pholus	Centaur	0.04 ± 0.13	2.59 ± 0.02	18
		(3)	(4)	(4)
1997 CU_{26}	Centaur	0.04 ± 0.01	1.74 ± 0.02	10
		(5)	(6)	(7)
1996 TL_{66}	KBO	?	1.15 ± 0.08	< 20
			(8)	(9)
1996 TO_{66}	KBO	?	0.72 ± 0.09	50
			(8)	(10)
1993 SC	KBO	?	$1.97 \pm 0.0.08$	< 20
			(8)	(11)

[a]Geometric albedo

[b]Depth of 2μm feature

Note. — References are given in parentheses beneath each quantity: (1) Campins et al. 1994, Altenhoff et al. 1995, Bus et al. 1996; (2) Hartmann et al. 1990, Davies et al. 1998; (3) Davies et al. 1993; (4) Cruikshank et al. 1998; (5) Jewitt and Kalas 1998; (6) McBride et al. 1999; (7) Brown and Koresko 1998; (8) Jewitt and Luu 1998; (9) Luu and Jewitt 1998; (10) Brown et al. 1999; (11) Brown et al. 1997.