SPECTROPHOTOMETRY OF KUIPER BELT OBJECTS 20000 VARUNA, 2000 EB_{173} AND CENTAUR 10199 CHARIKLO

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Abstract. Due to the distance, faintness, and very recent discovery of Kuiper Belt Objects (KBOs) and Centaurs, very little is known about the physical characteristics of these basic building blocks of the solar system. New intermediate-band photometry observations of KBOs and Centaurs suggest that absorption bands exist in the visible portion of their spectra, which could offer insights into the surface composition of these objects.

1. Introduction

Since the discovery of the first Kuiper Belt Object (KBO) in 1992 (Jewitt and Luu, 1993), a quest to understand the properties of this new class of objects has led to a large collection of broadband BVRI filter observations amassed by various groups. A broad range of colors of these objects has emerged from this campaign, ranging from red (increased reflectance with increasing wavelength) to grey. The grey objects have generally flat spectra similar to C-class asteroids, which prompted us to conduct a study to compare the spectral characteristics of red versus grey KBOs and Centaurs with the following arguments in mind.

The reflectance spectral characteristics of C-class asteroids are similar to those of carbonaceous chondrite meteorites, implying that carbonaceous chondrites originate from C-class asteroids. The terrestrial CM2 carbonaceous chondritic meteorite samples have been aqueously altered. They share distinctive features in the UVIVIS/NIR spectral region with the spectra of ∼50% of the C-class asteroids and related (B, F, G) subclasses.

Aqueous alteration is defined as the chemical alteration of material at low temperatures (< 320 K) by water (e.g., Zolensky and McSween, 1989). Water acts as a solvent to produce minerals such as oxides, hydroxides, sulfates and phyllosilicates. Evidence of aqueous alteration in asteroid spectra was first detected via an absorption feature observed at 3.0 μm. Structural hydroxyl (OH) and interlayer and adsorbed water in phyllosilicates are responsible for this broad absorption band, hereafter called 'water of hydration', observed in many C-class asteroids (Lebofsky, 1978, 1980).

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Vilas (1994) found a strong correlation (though not strict) between the presence of an absorption feature at 0.7 μm and the 3.0-μm water of hydration feature in phyllosilicates. This 0.7-μm band has been attributed to an Fe^{2+}–>Fe^{3+} charge transfer transition in oxidized iron present in phyllosilicates. Howell et al. (2001) showed that the presence of the 0.7-μm absorption feature always indicates the presence of the 3.0 μm water of hydration feature in an asteroid's spectrum, although the reverse is not necessarily true. Thus, the presence of the 0.7-μm absorption feature likely indicates the presence of water of hydration in phyllosilicates.

With a retrograde orbit and an inclination $i = 15°$, Saturnian satellite Phoebe has long been considered a candidate for a captured asteroid. The visible spectral properties of Phoebe in general appear very similar to C-class asteroid spectra. Vilas (1994) found that Phoebe showed the presence of the 0.7-μm feature on two of four dates that Eight-Color Asteroid Survey photometry of the satellite was obtained (Tholen and Zeliner, 1983), concluding that there is evidence for phyllosilicates formed as the result of aqueous alteration in the surface material on one side of Phoebe. Until recently, Phoebe has been considered to be a captured main-belt asteroid. Recent observations, however, have prompted investigators to suggest that Phoebe could be a captured Centaur (e.g., Hartmann et al., 1990; Brown, 2000). In particular, near IR photometry of Phoebe (Brown, 2000; Owen et al., 1999) suggest that water ice exists on the satellite's surface. Collectively, these spectral features suggest that the action of aqueous alteration has occurred on an object that was once a Centaur, though it is unclear when the aqueous alteration took place.

The potential discovery of minerals produced by aqueous alteration on Phoebe, a distant solar system object, implies that water played a role in its history, and perhaps water still exists in the object today. Taken with the arguments above regarding C-class asteroids with flat spectra, this poses interesting questions for KBOs and Centaurs: (a) do KBOs and Centaurs with flat reflectance spectra, like C-class asteroids, display an absorption band near 0.7 μm, implying they have undergone aqueous alteration? and (b) If Centaurs and/or KBOs show evidence of water of hydration suggesting the action of aqueous alteration, then what mechanism is responsible for heating them at such great distances from the Sun?

For aqueous alteration to take place, one must have water ice present, and an energy source to heat the water ice to a liquid water phase. Water ice has already been discovered in the Centaurs 2060 Chiron (Luu et al., 2000) and 10199 Chariklo (Owen et al., 1999; Brown, 1998; Brown and Koresco, 1998). Heating by electrical induction generated by solar wind interaction would not be expected to operate at those heliocentric distances. On the other hand, heating by ^{26}Al decay is a viable mechanism to heat the interior of objects such as these. In order to operate, however, this would require a rapid accretion of large bodies at that heliocentric distance. Hydrocryogenic alteration due to the action of 'unfrozen' water, is another possible mechanism. Here, thin (<100 Å) films of liquid pore water are stabilized, at temperatures as low as at least −20 °C (below the equilibrium freezing point), by the surface energy of solid materials (cf., Zolensky and McSween, 1989, and references therein).

Durda and Stern (2000) estimate that KBOs experience collisional processing regularly throughout their lifetimes ($\sim 10^{3-4}$ collisions/4.5 Gyr), which impact with energies high enough to either crater or disrupt these objects. They estimate that roughly 1/3 of a typical 100-km object will have been reworked due to collisions in the object's lifetime. This study suggests that collisions do occur with enough energy to induce aqueous alteration if water ice is present in these bodies, and that the re-worked surface may be patchy. Alternatively, nearby supernovae or massive passing O stars may have had an influence on heating comets in the Kuiper Belt in the last 4.5 billion years (Stern and Shull, 1988). In this light, we have conducted a search for evidence of aqueously-altered minerals on KBOs and Centaurs with solar-like colors similar to C-class asteroids.

2. Observations and Data Reduction

We observed two KBOs, 20000 Varuna and 2000 EB_{173}, and one Centaur, 10199 Chariklo on March 30 and 31, 2002 under photometric conditions. Data were obtained at the Kitt Peak National Observatory with the 4-m Mayall telescope and the Mosaic charge-coupled device (CCD) camera (2 × 2 binned). The scale of the resultant images is 0.52″/element and the field of view 36′ per side. We employed intermediate-band (A/AA 15–50) Beijing Arizona Taipei Connecticut filters with central wavelengths at 0.527, 0.666, 0.705, 0.755, 0.802, and 0.848 μm. Bandwidths ranged from 0.017–0.049 μm (Fan et al., 1996; Yan et al., 2000). This set of filters was chosen to map out the 0.7-μm region, which extends from 0.57 to 0.83 μm. Intermediate-band filters were chosen to allow us to obtain sufficient signal-to-noise on a 4 m-class telescope to search for the 0.7-μm absorption feature in these faint objects using techniques similar to those applied to C-class asteroids by Vilas (1994). Exposure times ranged from 200-900 s. Landolt standard stars were observed for calibration purposes, including solar analogue stars to allow us to calculate relative reflectance values (Landolt, 1992; Yan, 2000).

These data were reduced using the IRAF MSCRED package and the procedure outlined by Massey et al. (2002) and the NOAO mscguide. First, we accounted for crosstalk between the CCD chips. Next, the average bias for each frame was calculated from the overscan region of each individual frame and removed. A master bias frame was also created from a set of images and subtracted from each image to account for pixel-to-pixel variations. A master sky flat field was generated for each filter. The ghost pupil image was removed using the MSCPUPIL package. MSCIMAGE was employed to account for the variable pixel scale across the very wide field of view images produced by MOSAIC. Photometry was measured using the DAOPHOT/PHOT package. The final errors reported for colors of each object account for the photometric errors and the scatter in the individual measurements, added in quadrature.

3. Results

In Figure 1, we plot the relative reflectance divided by a solar analogue star and normalized to 1.0 at 0.527 μm. No absorption feature occurs in any of these spectra that suggests unambiguously the presence of the 0.7-μm absorption feature. We note that there are potential shallow absorptions in the visible spectra of Chariklo, but our resolution is not sufficient to detect any absorptions in Varuna or EB_{173}.

Observations of 10199 Chariklo vary slightly within the night of 31 March, and between the nights of 30 and 31 March. The repeatability of an absorption feature centered on the 0.705-μm and 0.802-μm filters on the night of 31 March suggests that this is a real feature. We note that the absorption is more pronounced in the Chariklo 31a spectrum. The seeing was notably better for the 31a observations (1–1.4$''$) than the 31b observations ($\sim$ 2$''$ We also note that seeing on 30 March ($\sim$3) was worse than 31 March. The short arc of the CCD spectrum of Chariklo obtained by Dotto et al. (2003) that overlaps in wavelength (0.5 to 0.75 μm) with our observations is consistent with our data.

Recall that the 0.7-μm feature attributed to oxidized Fe in phyllosilicates covers a spectral range from 0.57 to 0.83 μm. This is considerably wider than the range suggested by the photometry we have of Chariklo. An absorption feature ranging from 0.705 to 0.848 μm on 30 March may also be present in the spectrum of Chariklo (Figure 1). It is unlikely that these absorptions would be detected in broadband filters. The differences in spectral properties from one night to the next suggest variations in composition across it's surface. Since we are not aware of a rotational period for Chariklo, we cannot compare them temporally. If these nightly variations are real, then subtle spectral absorption signatures may be the key to detecting the rotational period of Chariklo.

Other options exist for the origin of any absorption features identified in spectrophotometry of Centaurs and KBOs, and there is no compelling reason to assume that these absorption features must be the result of aqueous alteration processes. Spectra with higher resolution across the same wavelength range could elucidate these more subtle features. Lazzarin et al. (2003) showed some narrowband spectra of 2000 EB_{173} that display absorption bands near 0.600 μm and 0.730 μm. These bands in these spectra did not resemble the wide 0.7-μm bands observed in C-class asteroids, but rather suggest the presence of an as-yet unknown material. Our spectral resolution precludes us from confirming these absorption bands.

Our current conclusion is that these intermediate-band filter spectra of these faint objects do not have sufficient spectral resolution to identify unambiguously any absorption feature narrower and shallower than the 0.7-μm phyllosillicate fea-

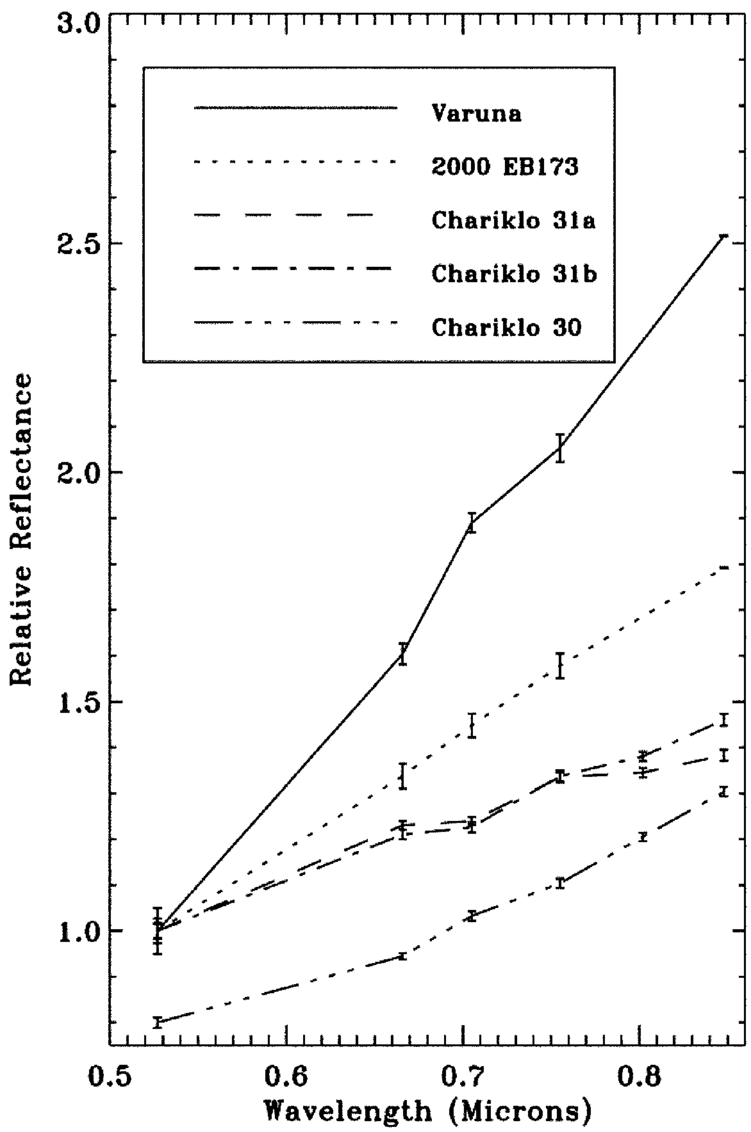

Figure 1. Observations of KBOs 20000 Varuna and 2000 EB_{173}, and Centaur 10199 Chariklo on for March 30–31, 2002. B. Spectral reflectance relative to solar analogue star and scaled to 1.0 at 0.527 μm. The data for March 30 of 10199 Chariklo are offset for clarity. Photometric errors are plotted.

ture, but they do hint at features. Narrowband reflectance spectra across a larger wavelength range would elucidate the presence of features unambiguously.

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