OPTICAL AND INFRARED REFLECTANCE SPECTRUM OF KUIPER BELT OBJECT 1996TL$_{66}$

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ABSTRACT

We have obtained optical (0.4 - 0.8 μm) and near-infrared (1.0 - 2.5 μm) reflectance spectra of the Kuiper Belt object 1996 TL$_{66}$. The spectra show no evidence for absorption features and are neutral across the full wavelength range. The spectrum of TL$_{66}$ is thus similar to that of the Centaur Chiron, but different from that of the Centaur Pholus. It also bears no resemblance to the spectrum of the Kuiper Belt object 1993 SC reported by Brown *et al.* (1997).

Subject headings: comets – solar system: formation

1. Introduction

The trans-Neptunian solar system is occupied by a vast population of small bodies known collectively as the Kuiper Belt (Jewitt, Luu, and Chen 1996). Kuiper Belt Objects (hereafter

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[2]Observations reported in this paper were obtained at the Multiple Mirror Telescope Observatory, a facility operated jointly by the University of Arizona and the Smithsonian Institution.

KBOs) are remnants from the accretion of the planets (Edgeworth 1949, Kuiper 1951) and, as such, probably contain some of the most primitive, thermally unprocessed materials in the known solar system (Bailey 1994). We have been conducting a wide-field, medium-depth survey along the ecliptic in search of bright KBOs suitable for physical study (Jewitt, Luu and Trujillo 1997). As a product of this survey, we recently identified an unusually bright KBO that seems to represent a new dynamical class (Luu *et al.* 1997). The object 1996 TL_{66} follows a highly elliptical, inclined orbit with perihelion and aphelion at $\sim$ 35 AU and $\sim$ 135 AU, respectively. Its orbit differs dramatically from those of other KBOs in both its size (semi-major axis a = 85 AU) and eccentricity (e = 0.59). The origin of 1996 TL_{66} is as yet unknown, but it may have been formed near Uranus or Neptune, then scattered outwards by encounters with these planets. If this hypothesis holds, it is presumably the first detected of a swarm of similar bodies that have survived the last 4.5 billion years in eccentric, trans-Neptunian orbits (the "Scattered Kuiper Belt"; Ip 1989, Torbett 1989, Ip and Fernandez 1991, Duncan and Levison 1997). We have estimated that the mass of such bodies is $\sim 0.5 M_E$ ($1\ M_E = 6 \times 10^{24}$ kg is the mass of the Earth), which possibly exceeds the mass in the classical Kuiper Belt (Luu *et al.* 1997). The brightness of TL_{66} (apparent red magnitude $m_R \sim 21$) implies a diameter near 500 km (assuming a 4% geometric albedo), and makes this object an excellent target for physical studies at optical and infrared wavelengths.

2. Observations

We have obtained low-resolution spectra of TL_{66} at both optical and near-infrared wavelengths with the 4.5-m Multiple Mirror Telescope (MMT) on Mt. Hopkins, Arizona, and the Keck I 10-m telescope on Mauna Kea, Hawaii, respectively.

(a) Keck observations

The near-infrared observations were taken at the $f/25$ forward Cassegrain focus of the Keck I telescope, using the NIRC facility camera (Matthews and Soifer 1994). NIRC contains a 256 x 256 pixel InSb array that can be switched in minutes from direct imaging at 0.15 arcsec per pixel (38" x 38" field of view) to slit spectroscopy at resolution $\lambda/\Delta\lambda \approx 100$. A north-south slit 0.68" wide by 38" long was used for all spectral observations. Spectral flat fields were obtained from a diffusely illuminated spot inside the dome. Imaging flat fields were constructed from the median of the night-sky images in each filter. Photometric and spectral calibration of the images was obtained from stars on the UKIRT Faint Standards list (Casali and Hawarden 1992). In addition, we observed the solar analogue stars 16 Cyg B and Hyades 64 (HD 28099) (Hardorp 1978, 1980) in order to cancel features specific to the solar spectrum.

We initially identified 1996 TL_{66} by its motion against the fixed stars at the predicted rate and in the predicted direction. Before each integration, the telescope was moved (while autoguiding on a nearby field star) so that the object was centered at the location of the slit, and its position confirmed by taking another image. The slit, grism and blocking filter were then inserted in the beam and we obtained a pair of spectra dithered along the slit by 13". Different grating settings and blocking filters were used to secure the JH and HK spectra. The integration times for individual JH and HK spectra were 360 sec and 300 sec, respectively. We found that non-sidereal tracking at the Keck was unreliable, so we re-checked the alignment of TL_{66} in the slit every 15 - 20 minutes.

(b) MMT observations

We used the Blue Channel spectrometer and a 3072 x 1024 pixel Loral charge-coupled device (CCD). The CCD was binned in the spatial direction, giving a spatial scale 0.6" per pixel along the slit. We employed a 1" $\times$ 180" slit and a 300 line/mm grating for all observations. The slit was kept vertical at all times to eliminate effects of differential atmospheric refraction. The natural dispersion of the 300 line/mm grating is 1.96 Å/pixel; with the 1" slit, the spectral resolution was measured at 6.1 Å FWHM. The total spectral coverage is 6000 Å, but here we restrict our analysis to the 4000 Å- 8000 Å portion due to the low throughput of the spectrograph at short wavelengths and spectral order overlap at long wavelengths. Flat field images were obtained using an internal quartz lamp; anticipating the long exposure times, dark emission images were also taken for calibration purposes. Flux calibration was achieved with observations of the Kitt Peak National Observatory IRS stars taken at similar airmasses as the TL_{66} spectra. As with the infrared observations, we also observed the solar analogues 16 Cyg B and Hyades 64 in order to cancel solar features in the spectrum of TL_{66}.

The optical, JH and HK spectra of 1996 TL_{66} were necessarily taken on different days (Table 1), raising the question of how to reduce the spectra to a common scale. We determined the appropriate normalization of the JH and HK spectra using broadband JHK photometry secured with NIRC on UT 1997 Sep 08. The optical spectrum was normalized to V band photometry taken at the University of Hawaii 2.2-m telescope on UT 1997 Sep 24 (the details are being prepared for publication). The bridge from the optical to the IR spectra was determined by assuming that TL_{66} exhibits no photometric variations due to rotation. We note that, in support of this assumption, optical photometry of TL_{66} over 6 hours on UT 1996 October 15 shows no evidence for rotational modulation of the apparent brightness larger than 0.05 mag. The resulting reflectance spectrum is shown in Figure 1. To better guide the eye, the optical portion of the spectrum has been binned by 0.025 μm. The Figure also shows photometry of TL_{66} obtained with various broadband filters (BVRI, JHK). There is very good agreement between the broadband data and the spectral data. In Table 2 we give the normalized reflectivities as a function of wavelength.

3. Discussion

As can be seen in Fig. 1, the reflectance spectrum of 1996 TL_{66} is nearly neutral in the $0.4 \leq \lambda \leq 2.5$ μm wavelength range. Reflectivity gradients determined from the separate spectra are $S'(0.40 - 0.80\ \mu\text{m}) = (-1.1 \pm 0.7)$ %/1000 Å, $S'(0.95 - 1.60\ \mu\text{m}) = (-0.9 \pm 0.9)$ %/1000 Å and

$S'(1.4 - 2.5\ \mu\text{m}) = (-1.5 \pm 0.4)\ \%/1000$ Å, respectively. TL_{66} thus resembles the Centaur object 2060 Chiron, whose reflectance spectrum is neutral to slightly blue in the optical (Luu and Jewitt 1990) and near-infrared (Hartmann *et al.* 1990). The flat optical spectrum of TL_{66} stands in stark contrast to the highly reddened Centaur 5145 Pholus (Mueller *et al.* 1992, Fink *et al.* 1992, Luu 1993, Davies *et al.* 1993).

The overtone and combination vibrational bands of several common molecular bonds (e.g., O-H, N-H, C-H) fall in the near infrared portion of the spectrum, and we searched for such solid state absorptions in the NIRC spectra. However, 1996 TL_{66} shows no absorption features in the near-infrared and so bears no resemblance to the spectra of common ices (see Fig. 2). A comparison of TL_{66} with Pluto, Chiron and Pholus is made in Fig. 3. Again, it can be seen that the spectrum of TL_{66} is reminiscent of the featureless near-infrared spectrum of Chiron and differs remarkably from the spectrum of Pholus. The spectrum of Pholus shows strong absorption features at 2.07, 2.27 μm (Davies *et al.* 1993) and a weaker absorption at 1.72 μm (Luu, Jewitt and Cloutis 1994). These features, although not yet convincingly identified with specific materials, are often taken to suggest a hydrocarbon-rich surface (Cloutis 1989, Cruikshank *et al.* 1998), a hypothesis which is consistent with the low optical geometric albedo of Pholus (0.04 at 0.55 μm, Davies *et al.* 1993). We also note that the near-infrared spectrum of TL_{66} is very different from the spectrum of the KBO 1993 SC (Brown *et al.* 1997). The latter was reported to show molecular features similar to those seen on the surfaces of Pluto and Triton, despite being 3 times fainter than TL_{66} and being observed at a much lower signal-to-noise ratio. The marked difference between these two KBOs is intriguing and deserves more scrutiny.

Like 1996 TL_{66}, Pluto's satellite, Charon, possesses a neutral optical spectrum (Binzel 1988), yet has been reported to carry water ice frost on its surface (Buie *et al.* 1987). We use numerical simulations to assess the sensitivity of the NIRC spectrum of 1996 TL_{66} to molecular ice absorptions. Our spectrum has SNR of 6 to 7 per pixel in the K region. At this SNR, we find that absorption features due to pure ice would be clearly visible. We thus conclude that the absence of measurable absorptions in the spectrum of TL_{66} precludes the possibility that its surface is coated by pure water ice or snow. The absence of strongly blue V-J, J-H and H-K colors supports this conclusion, since pure ices and snows tend to be very blue (Clark 1982). However, we cannot rule out dirty water ice in which the vibrational features are damped by even tiny amounts of absorbing impurities. We also considered a linear mixing model in which the surface of TL_{66} is taken to be divided into regions of pure water ice and pure "dirt", the latter having a uniform continuum reflectance equal to the average reflectance of water ice in the $2.0 \leq \lambda \leq 2.4\ \mu$m wavelength range. After testing a wide range of ice/dirt ratios we found that, at SNR = 6, we would have detected water bands if more than 10% of the surface had been covered by pure water ice. Deep, solid-state features like those due to methane on Pluto would also have been detected if present on TL_{66}. It is more difficult to detect CO_2 due to the narrowness of its features, and we cannot rule out its presence based on the current spectrum.

Overtones of water vibrational bands are present in the spectra of many minerals. We compared 1996 TL_{66} with the reflectance spectra of 25 tar sand samples (provided by Ed Cloutis, University of Winnipeg). There is no resemblance because (a) many tar sands show features that TL_{66} does not, and (b) the tar sands are systematically redder than TL_{66}.

KBOs and Centaurs are expected to possess irradiation mantles due to long-term exposure to cosmic rays; these irradiation mantles presumably cause the extremely red colors of some objects (e.g., Pholus). To explain the neutral colors of other KBOs and Centaurs (e.g., Chiron, 1994 ES_2), we proposed that their irradiation mantles have been partially buried, either by fresh material excavated by collisions (Luu and Jewitt 1996) or, in the case of Chiron, by fallback debris (Luu 1993). This hypothesis predicts that the surface of 1996 TL_{66} should have been recently covered with freshly excavated material likely to show absorption features due to incorporated ice. However, no such features are seen. The absence of absorption features could mean that the collisional resurfacing hypothesis is incorrect, or it could mean that the excavated material consists of impure ice. The featureless near-infrared spectrum of Chiron may be similarly explained. We thus conclude that the spectral properties of the 3 KBOs so far observed (Pluto, 1993 SC, 1996 TL_{66}) are very different, and that there is no single explanation for these differences. More observations are needed to explore the range of spectral types in the Kuiper Belt and to understand the origin of the observed differences.

4. Summary

1. We have obtained 0.4 to 2.5 μm spectra of 1996 TL_{66}. In both the optical and the near-infrared, the reflectance spectrum of 1996 TL_{66} is nearly neutral, much like that of the Centaur 2060 Chiron.

2. The reflectance spectrum of 1996 TL_{66} shows no spectral features. Features like those already observed on Pluto, Pholus, and 1993 SC would have been detected in our data had they been present.

3. Pure water ice can cover at most 10% of the surface area of 1996 TL_{66}. The spectrum cannot rule out the presence of ices contaminated by absorbing impurities.

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FIGURE CAPTIONS

Figure 1. Optical and infrared reflectance spectrum of 1996 TL_{66}, normalized at 0.55 μm. The optical spectrum has been binned by 0.025 μm, the infrared spectrum by 0.1 μm. Data from broadband filters are also shown, and are consistent with the spectrum. The bandpasses of the broadband filters are indicated on the plot.

Figure 2. Infrared reflectance spectrum of 1996 TL_{66} compared to spectra of H_2O, CO_2, NH_3, and CH_4 ices (Fink and Sill 1982, Larson and Fink 1972). All spectra have been normalized at 2.2 μm and the ice spectra have been offset for clarity. There is no evidence for spectral features in the spectrum of TL_{66}.

Figure 3. 1996 TL_{66} compared with the Centaurs Chiron and Pholus, and Pluto (Owen *et al.* 1993). All spectra have been normalized at 2.2 μm, and those of Chiron, Pholus, and Pluto have been offset for clarity. The spectrum of 1996 TL_{66} is flat and featureless like that of Chiron, and lacks the absorption bands seen in Pholus and Pluto.