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OPTICAL-INFRARED SPECTRAL DIVERSITY IN THE KUIPER BELT

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ABSTRACT

We have measured the optical and infrared colors of five Kuiper belt objects to search for evidence of spectral diversity among these bodies. We find extreme differences, especially in the measured $V-J$ color indices, that indicate a wide range of surface compositions in the Kuiper belt.

Key words: comets: general — minor planets, asteroids

1. INTRODUCTION

Optical surveys of the ecliptic have revealed a large and growing number of objects in the region beyond Neptune (Jewitt & Luu 1993, 1995; Jewitt, Luu, & Chen 1996; Irwin, Tremaine, & Żytkow 1995; Williams et al. 1995). These "Kuiper belt objects" (KBOs) are thought to be ice-rock remnants that have survived from the epoch of formation of the gas-giant planets (Edgeworth 1949; Kuiper 1951; Bailey 1994). They may also supply the short-period comets (see, e.g., Fernández 1980; Duncan, Quinn, & Tremaine 1988) and, through collisions, may be a source of interplanetary dust (Backman, Dasgupta, & Stencel 1995; Stern 1996). Presently, 60 such objects are known, ranging from 2200 km diameter Pluto to numerous 100 km diameter objects at the limit of optical surveys.

Physical observations of KBOs are limited by the faintness of these objects. Luu & Jewitt (1996) used optical photometry to show that the KBOs are spectrally diverse. Measured optical colors range from neutral ($V-R \approx 0.35$) to very red ($V-R \approx 0.9$). This dispersion of optical colors implies a diversity of surface compositions on the KBOs. It is possible that compositional differences are intrinsic to KBOs, just as the main-belt asteroids have different compositions resulting from different formation locations and thermal histories. However, this scenario seems difficult to reconcile with the current view of the early outer solar system, in which temperatures are low ($\sim$40 K at Neptune) and temperature gradients are small. As an alternative, Luu & Jewitt (1996) suggested that collisional resurfacing might instead account for the color diversity of KBOs. In this scenario, the surface color and albedo of a KBO result from a competition between opposing agencies and are time dependent. Cosmic-ray bombardment causes a progressive darkening and reddening of surface materials, resulting in the formation of an irradiation mantle. Occasionally, impacts will puncture the irradiation mantle and excavate debris from below, coating part or all of the KBO surface with fresh, less red (possibly ice-rich) material. This process will cause large color and albedo variations provided that the timescales for radiation processing and collisional resurfacing are of the same order. Unfortunately, neither timescale is well known, even to order of magnitude, and the role of collisional resurfacing is unclear. Green et al. (1997) later obtained an essentially compatible result, while Tegler & Romanishin (1997) believe the evidence for spectral diversity is "tantalizing, but not yet firm."

In this paper, we present new broadband optical and infrared observations of KBOs that confirm and extend the evidence for spectral diversity in the Kuiper belt. Broadband reflectance spectra are only weakly diagnostic of composition (Clark 1982) but have the advantage that they provide a practical and robust measure of spectral differences among KBOs.

2. OBSERVATIONS

Optical observations were taken at the f/10 focus of the University of Hawaii (UH) 2.2 m telescope on Mauna Kea. We used a Tektronix 2048 × 2048 pixel CCD with 0″.219 square pixels and a 7′.5 × 7′.5 field of view. Sensitivity variations across the CCD were removed by dividing by a flat-field calibration constructed from spatially offset images of the twilight sky. Measurements were obtained through Johnson (*BV*) and Kron-Cousins (*RI*) filters and calibrated by imaging standard stars from Landolt (1992). We used stars with $0.3 < V-R < 0.9$ to approximately match the range of colors measured among other KBOs (Luu & Jewitt 1998; Green et al. 1997). We took two or three images of each object in each filter. In the 300 s integrations employed, the typical object trailed by about 0″.25 relative to the fixed stars. Subsequent measurements showed point-spread functions (PSFs) with an intrinsic width of 0″.5–0″.6 FWHM but with elongation to 0″.7 east-west, due to periodic error in the telescope drive. A few images were affected adversely by wind-driven vibration of the telescope and were rejected from subsequent consideration. Magnitudes of KBOs were determined within synthetic apertures typically 1″.8–2″.2 in diameter. These apertures were selected following examination of the PSF and are communsurate with the good seeing experienced on Mauna Kea. The use of small apertures does make the photometric stability vulnerable to gross changes in the PSF. Accordingly, we monitored the PSF during the course of the night to ensure its stability. In a few cases, we enlarged the aperture diameter to correct for an inflated PSF, but in no case did the measured magnitudes change by more than ± 0.05 from this effect. We visually examined each image to search for cosmic-ray and background galaxy contamination of the

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TABLE 1

OPTICAL OBSERVATIONS (UT 1997 SEPTEMBER 23 AND 24)

Object	R^{a} (AU)	Δ^{b} (AU)	α^{c} (deg)	$m_R(1, 1, 0)^{d}$	B	V	R	I
1993 SC	34.48	33.48	0.19	6.71	23.65 ± 0.04	22.71 ± 0.04	22.03 ± 0.02	21.35 ± 0.04
1996 TO_{66}......	45.75	44.75	0.05	4.52	21.99 ± 0.05	21.40 ± 0.03	21.08 ± 0.05	20.72 ± 0.05
1996 TP_{66}	26.43	25.52	0.93	6.97	22.60 ± 0.05	21.80 ± 0.05	21.15 ± 0.04	20.44 ± 0.02
1996 TS_{66}	38.88	38.08	0.92	6.11	23.36 ± 0.05	22.43 ± 0.08	22.00 ± 0.08	21.33 ± 0.09
1996 TL_{66}	35.15	34.33	0.94	5.32	21.54 ± 0.02	20.96 ± 0.05	20.83 ± 0.04	20.29 ± 0.02

[a] Heliocentric distance.
[b] Geocentric distance.
[c] Phase angle.
[d] Absolute red magnitude, defined as $m_R(1, 1, 0) = R - 5 \log R\Delta - 0.04|\alpha|$, where R and Δ are in AU.

TABLE 2

INFRARED OBSERVATIONS (UT 1997 SEPTEMBER 7 AND 8)

Object	R^{a} (AU)	Δ^{b} (AU)	α^{c} (deg)	J	H	K
1993 SC	34.47	33.54	0.64	20.74 ± 0.07	20.34 ± 0.19	20.38 ± 0.05
1996 TO_{66}......	45.75	44.78	0.33	20.68 ± 0.08	20.89 ± 0.15	20.08 ± 0.05
1996 TP_{66}	26.43	25.66	1.43	19.59 ± 0.05	19.42 ± 0.06	19.40 ± 0.07
1996 TS_{66}	38.88	38.28	1.20	20.52 ± 0.05	19.87 ± 0.05	...
1996 TL_{66}	35.16	34.52	1.28	19.81 ± 0.06	19.46 ± 0.1	19.50 ± 0.05

[a] Heliocentric distance.
[b] Geocentric distance.
[c] Phase angle.

synthetic apertures. The sky brightness was measured within a contiguous annulus 8".8 in outer diameter. We observed the KBOs and Landolt stars at small air masses (<1.3) and with air-mass differences not larger than ~0.1. Consequently, the extinction corrections were negligible (in comparison with the final photometric uncertainties) in all filters but B.

Near-infrared observations were taken at the f/25 forward Cassegrain focus of the 10 m Keck I Telescope, also on Mauna Kea. The NIRC facility camera (Matthews & Soifer 1994) was employed to obtain images through standard J, H, and K filters. This is a 256 × 256 pixel InSb array with 0".15 pixels and a 38" × 38" field of view. Flat fields were constructed for each filter using the median of the (dark-subtracted) science images. Gross sky subtraction was obtained by chopping 10" to the east, a distance small enough that the target object was always imaged on the array. Photometric calibration was obtained from stars on the UKIRT faint standards list (Casali & Hawarden 1992). The seeing was a remarkably good 0".35 to 0".50 FWHM. Photometry was performed generally with photometric apertures 1".2 in diameter, with sky subtraction from a contiguous annulus 7".8 in outer diameter. Again, we monitored the PSF to check for variations and examined each image for evidence of contamination by background galaxies and defective pixels. As at the UH telescope, KBOs were recognized by their slow retrograde motions (at rates in the range 3"–4" hr^{-1}) relative to the fixed stars.

3. DISCUSSION

The photometry is summarized in Tables 1 and 2, while color indices are listed in Table 3. Photometric errors were estimated from the scatter among repeated measurements and largely reflect uncertainty in the level of the surrounding sky. In some cases, contamination by faint background galaxies, or by wings of bright field stars, is suspected and has inflated the estimated error. For example, the K-band measurement of 1996 TS_{66} was severely compromised in this way and has been omitted. As a check of the photometry, we observed 624 Hektor and obtained $J-H = 0.41 \pm 0.03$ and $H-K = 0.18 \pm 0.03$, both consistent with the values given by Veeder et al. (1983). Recent grism spectra of 1996 TL_{66} taken with the Multiple Mirror and Keck I Telescopes (Luu & Jewitt 1998) are consistent with the neutral $BVRIJHK$ colors presented here. For 1993 SC, our measured $V-J = 1.97 \pm 0.08$ is consistent with an independent determination of $V-J = 2.07 \pm 0.1$ (Davies, McBride, & Green 1997). Our measured $H-K = -0.04 \pm 0.19$ is not consistent with the reported brightening of 1993 SC by a factor of 2 (0.75 mag) from 1.6 to 2.2 μm in a slit spectrum by Brown et al. (1997).

We computed reflectivities from the optical and near-infrared photometry using the adopted solar colors

TABLE 3

BROADBAND COLORS

Object	$V-J$	$J-H$	$H-K$
1993 SC	1.97 ± 0.08	0.40 ± 0.20	-0.04 ± 0.19
1996 TO_{66}......	0.72 ± 0.09	-0.21 ± 0.17	0.81 ± 0.15
1996 TP_{66}	2.21 ± 0.07	0.17 ± 0.06	0.02 ± 0.09
1996 TS_{66}	1.91 ± 0.09	0.65 ± 0.07	...
1996 TL_{66}	1.15 ± 0.08	0.35 ± 0.14	-0.04 ± 0.11

NOTES.—Listed uncertainties in $V-J$ do not include possible errors due to rotational brightness variations in the interval between the optical and infrared observations. Brightness variations due to the change in observing geometry between the optical and infrared observations (see Tables 1 and 2) are negligible

$B-V=0.67$, $V-R=0.36$, $R-I=0.35$, $V-J=1.08$, $J-H=0.29$, and $H-K=0.06$ (Hartmann, Cruikshank, & Degewij 1982; Hartmann et al. 1990; Hardorp 1980). Slightly different solar colors have been advanced elsewhere (e.g., Campins, Rieke, & Lebofsky 1985), but the differences are, for the purposes of this paper, unimportant. In addition to the random errors carried from Tables 1 and 2, an additional uncertainty results from possible rotational variations of the KBOs during the interval between the optical and infrared observations. In this regard, we note that 1993 SC is known to lack a measurable rotational light curve (Davies et al. 1997; Tegler et al. 1997). Our own (unpublished) observations of KBOs at different epochs suggest that rotational modulation of the brightness is typically less than a few tenths of a magnitude, although individual objects may of course exceed this. The reflectivities, normalized to the V-band observation in each case, are shown in Figure 1. Reflectivities of 2060 Chiron (Hartmann et al. 1990) and 5145 Pholus (Mueller et al. 1992; Davies, Sykes, & Cruikshank 1993) are also plotted. The spectrum of Centaur 1995 GO (not shown), with $V-J=1.72\pm0.18$, is intermediate between those of Chiron and Pholus (Weintraub, Tegler, & Romanishin 1997).

The basic result to be drawn from Figure 1 is that pronounced differences exist among the 0.4 μm $\leq \lambda \leq$ 2.2 μm spectra of KBOs. The differences are too large (up to 1.5 mag in $V-J$) to be caused by errors of measurement and support the conclusion, reached earlier from optical data alone, that the surfaces of KBOs are compositionally varied

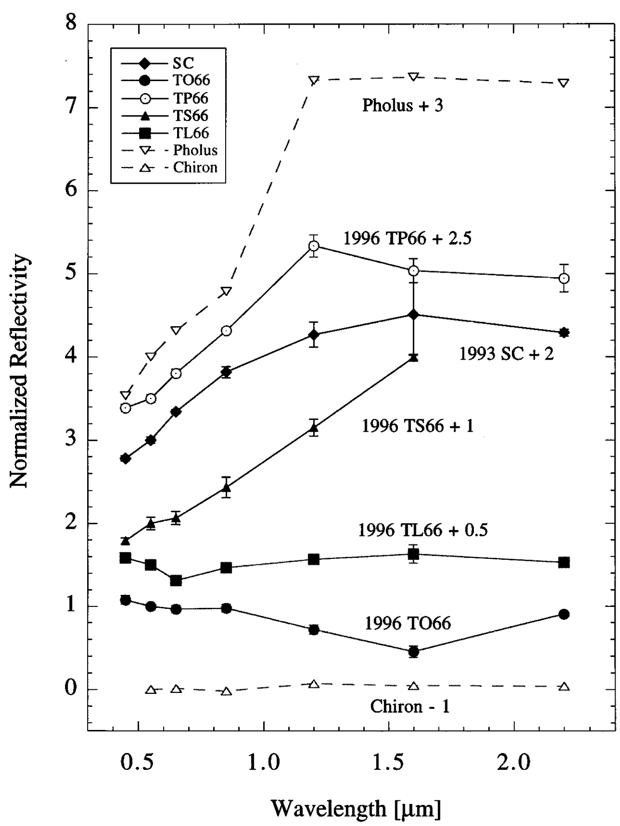

FIG. 1.—Normalized reflectivity vs. wavelength for the five Kuiper belt objects of this study. The KBOs are vertically offset for clarity but preserve a fixed scale. Reflectivities of Centaur objects 2060 Chiron and 5145 Pholus are shown for comparison.

(Luu & Jewitt 1996; Green et al. 1997). Some, typified by 1996 TL_{66} and 1996 TO_{66}, are neutral or slightly blue across the full wavelength range. These objects are spectral analogs of 2060 Chiron (Fig. 1). Other KBOs (e.g., 1993 SC and 1996 TP_{66}) show strong reddening from 0.4 to 1.2 μm but are spectrally flat, or slightly blue, at longer wavelengths. These objects more closely resemble 5145 Pholus. It is clear that the $V-J$ color index forms a robust tool with which to distinguish KBOs of different spectral types. Given a larger observational sample, it might ultimately be possible to classify KBOs using their broadband colors and, so, to begin to explore the origins of the spectral differences.

It is not possible to make unique compositional diagnostics based on broadband colors alone. However, the broadband data effectively rule out pure ices and frosts, which have $J-H$ and $H-K \leq -0.2$ (Clark 1982) and which are distinctly blue in the wavelength region from V to J. Ice-covered Pluto, for example, has $V-J=0.88$, $J-H=-0.23\pm0.1$, and $H-K=-0.44\pm0.1$ (Hartmann et al. 1982). The neutral colors of 1996 TL_{66} and 1996 TO_{66} are compatible with a wide range of surface materials, including dirty water ice (see sample 11 of Clark 1982), carbon lampblack (sample 43), and some refractory minerals (e.g., aubrite; sample 31). The steep, red 0.4–1.2 μm reflectance spectra of 1996 TP_{66}, 1993 SC, and 1996 TS_{66} are incompatible with these materials but instead resemble carbon-rich compounds, including fine-grained charcoal (sample 10), organic extract from the Murchison meteorite (sample 34; cf. Cloutis 1989), and assorted "tholins" (Wilson, Sagan, & Thompson 1994). Brown et al. (1997) report a low signal-to-noise ratio detection of solid-state absorption bands in a 1 hr integration on 1993 SC. If these absorptions were confirmed, Figure 1 would suggest that related features might profitably be sought in the brighter but colorimetrically similar object 1996 TP_{66}.

Figure 2 shows a plot of the absolute red magnitude $m_R(1, 1, 0)$ versus the $V-J$ color index of KBOs. A trend is apparent, with the redder $V-J$ colors being associated with fainter absolute magnitudes (corresponding to smaller diameters). The line shows a weighted least-squares fit to the KBO data. The linear correlation coefficient is $r_{\rm corr} = 0.981$ ($N=5$), and the probability that a larger correlation coefficient might be obtained by chance from random, uncorrelated data is $P(r > r_{\rm corr}) = 0.003$. The trend is therefore statistically significant at the 3 σ (99.7% confidence) level. If confirmed, it would suggest that surface color is a function of object size [represented by its proxy, $m_R(1, 1, 0)$]. However, we find it surprising that such a large color variation should occur over only 3 mag in $m_R(1, 1, 0)$ (corresponding to diameters different by only a factor of 3, at constant albedo). The resurfacing model nominally predicts an inverse correlation between the albedo and the $V-R$ color index that is qualitatively consistent with the measured trend (Luu & Jewitt 1996). However, since we cannot measure albedo, it is impossible to disentangle its contribution to $m_R(1, 1, 0)$, and we cannot use Figure 2 to test the resurfacing model. Color-size relations might also result from preferential retention of surface frosts on the larger bodies, as in the case of Pluto. We did not find significant color–absolute magnitude correlations in our *BVRI* photometry of fainter KBOs (Luu & Jewitt 1996). This could be because the wavelength baseline provided by the optical data alone is too short, or because the KBOs observed in the earlier work were, on average, smaller than

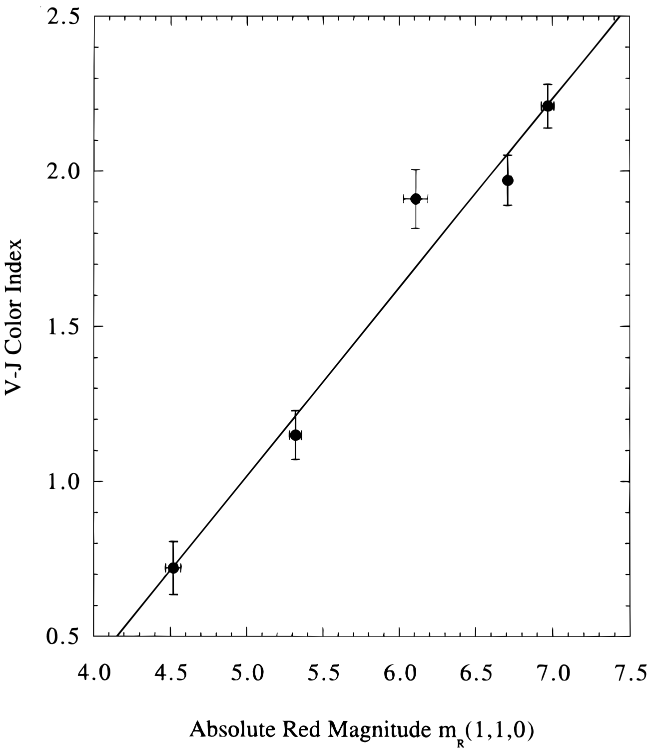

FIG. 2.—Absolute red magnitude $m_R(1, 1, 0)$ vs. $V-J$ color index for KBOs (*circles*). The line shows the weighted least-squares fit.

the ones observed here, or because the correlation in Figure 2 is a statistical fluke. Before speculating on this subject, however, it would seem prudent to await additional broadband measurements of other KBOs (over a wider size range) to either confirm or refute the trend seen in the first five targets.

4. SUMMARY

1. We have obtained new broadband photometric observations of five Kuiper belt objects in the 0.4–2.2 μm wavelength range. These observations support earlier conclusions derived from optical data by showing a wide range of spectral types in the Kuiper belt. A wide range of surface compositions and, presumably, of albedos is implied. The $V-J$ color index provides the best discrimination among the different surface types.

2. The neutral and red colors of KBOs rule out surfaces composed of pure ices and frost but are still compatible with a wide range of substances, including dirty water ice (1996 TO_{66}, 1996 TL_{66}) and assorted carbon-rich compounds (1993 SC, 1996 TP_{66}, 1996 TS_{66}). We cannot yet identify specific materials on the KBOs.

3. The Kuiper belt observations show a correlation between the $V-J$ color index and the absolute red magnitude, $m_R(1, 1, 0)$, that is significant at the $\sim 3\ \sigma$ (99.7%) confidence level. This correlation may indicate that the surface compositions of KBOs are related to their diameters, possibly as a result of the preferential retention of frost by large objects or of the size-dependent effects of collisional resurfacing. However, the current sample is small, and we feel that a larger sample must be obtained before the observed correlation can be considered secure.

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