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The Extraordinary Colors of Trans-Neptunian Objects 1994 TB and 1993 SC

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We present B–V and V–R colors for trans-neptunian objects (TNOs) 1994 TB and 1993 SC. We have found that these TNOs have colors almost as red as 5145 Pholus which are therefore consistent with surfaces rich in complex organic molecules. We have measured B–V colors of 1.10 ± 0.15 and 1.27 ± 0.11 for 1994 TB and 1993 SC, respectively, as well as V–R colors of 0.68 ± 0.06 and 0.70 ± 0.04 for 1994 TB and 1993 SC, respectively. Currently, there are only four TNOs with published broadband colors (1992 QB1, 1993 FW, 1993 SC, and 1994 TB). TNO colors range from solar (a single V–R measurement of 1993 FW in the literature) to nearly the reddest objects in the solar system (our measurements of 1993 SC and 1994 TB). Although we have concluded 1993 SC is a very red TNO, a measurement in the literature has suggested that there is nothing special about the color of 1993 SC. Because there are so few TNOs with color measurements and because colors for 1993 SC are inconsistent, we cannot say yet with any certainty whether the surfaces of TNOs exhibit a diversity of colors and hence a diversity of surface compositions.

1. INTRODUCTION

Edgeworth (1949) and Kuiper (1951) were the first to hypothesize the existence of trans-neptunian objects (TNOs). They rationalized that planetesimal formation in the solar nebula could not have ended abruptly near the orbit of Neptune and that the low density of nebular material beyond 40 to 50 AU could have supported the formation of small bodies (less than a few hundred kilometers in diameter). Edgeworth and Kuiper suggested that the solar system beyond Neptune consisted of progressively smaller icy bodies (comets) confined near the plane of the ecliptic (the Kuiper Belt).

In 1992, Jewitt and Luu (1993) carried out a survey of 0.7 square degrees of the sky to a limiting magnitude of R ~ 25 and discovered the first TNO (1992 QB_1). Thirty-six TNOs have been discovered as of June, 1996. The TNOs have effective diameters ranging from 100 to 400 km (Jewitt and Luu 1995), making them significantly larger than typical comets such as 1P/Halley (15 × 8 km; Keller *et al.* 1987). Jewitt and Luu have estimated that there are ~35,000 TNOs larger than 100 km in the 30 to 50 AU heliocentric distance range.

Almost nothing is known about the chemical nature of the TNOs that have been discovered so far. It is possible, perhaps likely, that they are mostly similar in composition to the short-period comets that we believe are derived from the Kuiper Belt, though cosmic-ray processing may have greatly altered their surfaces. However, TNOs span wide ranges in size and heliocentric distance and some or all of them may have compositions very different from those of short-period comets. Composition may also be a function of heliocentric distance, thereby providing a signature of formation mechanisms, as in the asteroid belt. It is possible that TNOs have surfaces that are (1) composed of pure H_2O ice (similar to Pluto's moon Charon), (2) similar to carbonaceous chondritic material, or (3) similar to that of short period comets (frozen H_2O, CO, CH_3OH, CO_2, NH_3, CH_4, HCN, and silicates) but richer in complex organic molecules as a result of cosmic ray and solar wind bombardment of their surfaces.

In this paper we report B, V, and R band photometry of the TNOs 1994 TB and 1993 SC. Our measurements allow us to constrain the surface composition of these two TNOs.

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2. OBSERVATIONS

Observations were obtained during four nights (24–27 November 1995 UT), using the Steward Observatory 2.3-m telescope on Kitt Peak. The 1200 × 800 pixel Loral–Fairchild CCD was used in a 2 × 2 binning mode, yielding a 600 × 400 pixel image, covering 3.0 × 2.0 arcmin on the sky at 0.3 arcsec pixel^{-1}. This CCD has outstanding quantum efficiency, particularly in the blue, where the QE exceeds 95%. This greatly aided our blue photometry of these faint objects. The V and R filters provided a superb match to the standard Kron–Cousins–Landolt system V–R colors, with a transformation slope of unity and negligible offset between instrumental and standard colors. The B and V filters yielded a transformation slope different form unity by only about 5%, and the overall fit to the standard system was again excellent.

Observing conditions were variable. The first night was photometric. Observations were obtained of the standard star field in M 67 (Schild 1983) and several Landolt (1992) standard star fields (PG 0231 + 051 and PG 2213 − 006). During the remainder of the run, there is evidence in the data of variable thin clouds, with cloud extinction of 0.2 mag at most. As discussed below, our photometry procedure is not affected by these clouds, as we reference magnitudes to secondary standard stars whose magnitudes were determined on the first night, and also during a separate run described below.

The initial CCD reductions were fairly standard, using a combination of twilight and dark sky observations for flatfielding. After bias subtraction and flatfielding, the regions around the TNO and secondary standard star in each image were searched visually for nearby cosmic rays. Cosmic rays on this chip were easy to spot, and usually affected only 3 or 4 pixels. Cosmic rays near the objects of interest were replaced by the average of neighboring good pixels. One image contained a cosmic ray coincident with the center of a TNO, and this image was discarded.

To increase the signal to noise, groups of individual 600 sec (V and R filter) or 900 sec (most B filter images) frames taken together in time were averaged. Groups usually consisted of three images, but some had two or four. Because of the motion of the TNOs, two averaged images of each group were produced. One averaged image had the individual frames shifted so that the stars were registered, the other so that images of the moving TNO were registered. (Typical TNO motion was about four pixels per hour.) By averaging in this way, the motion of the TNO from frame to frame did not contribute to any degradation of the TNO image on the TNO registered image. The motion of the TNO during each individual image did contribute to smearing, but this motion was small, less than 1 pixel.

For each TNO, we chose an isolated field star common to all the images of that TNO. These stars were 3 to 4 magnitudes brighter than the TNO, but with peak count rates well below any possible nonlinear part of the CCD response. Standard colors and magnitudes were obtained for these stars using the data from the first night of the Steward run, as well as a December, 1995 Lowell run. For the Steward data, an aperture of 8 arcsec diameter (12 pixel radius) was used for the standard stars and the secondary standard stars. Given the typical seeing (1.5 arcsec FWHM) this aperture encompassed essentially all the light of the stars. Comparison of the secondary standard stars with other stars in the same fields was used a check for any variability of the secondary standard during the run—none was found.

A completely independent check on the magnitudes of our secondary standard stars was provided by observations of the 1994 TB and 1993 SC fields on the night of 8 December 1995 UT, with the 0.76-m telescope of Lowell Observatory and the Photometrics CCD of the National Undergraduate Research Observatory. Observations were obtained of the Landolt standard star field PG 0231 + 051. The magnitudes derived for the secondary stars were in excellent agreement with those found on the first night of the November Steward run.

The TNOs are so faint that the uncertainty in their magnitudes is dominated by sky noise. Under such conditions, it is common in stellar photometry to use a rather small aperture to perform the instrumental magnitude measurement, in order to minimize the sky noise, and to make a correction to the "total" magnitude using observations in small and large apertures of a brighter star in the same field. We essentially used this method to get instrumental magnitudes for the TNOs. For each averaged TNO image, we measured the TNO with a small aperture (2.4 arcsec diameter; 4 pixel radius) on the image with the TNO registered, and measured the secondary standard field star with the same aperture on the averaged frame with the stars registered. This yields a magnitude difference between TNO and secondary standard star which should be unaffected by seeing variations, tracking errors, variable clouds, or focus problems. Aperture photometry was done with the PHOT task in the IRAF DIGIPHOT package. For all photometry, the sky value was found in an annulus from 20 to 33 pixels radius. The sky value was the peak of a gaussian fit to the histogram of pixel values in the sky annulus. If necessary, the sky annulus was first cleaned of objects which might bias the sky measurement by replacing them with a patch of nearby sky.

To check on the accuracy of our quoted uncertainties in the V magnitudes of the TNOs, we measured the V magnitude of an isolated star found on the same frames as the TNOs. For 1994 TB, the star was about as bright as the TNO at its brightest, while for 1993 SC the star was several tenths of a magnitude fainter than the TNO. For the 1994 TB star, the scatter in magnitudes was 0.06, while

TABLE I
BVR Magnitudes for 1994 TB

UT[a]	B	V	R
02.83			22.41 ± 0.06
04.40		23.37 ± 0.11	
26.02			22.39 ± 0.06
26.68		23.03 ± 0.08	
27.45	24.13 ± 0.16		
50.12			22.63 ± 0.06
50.72		23.05 ± 0.08	
51.27		23.14 ± 0.08	
51.87			22.49 ± 0.06
73.77			22.67 ± 0.10
75.00	24.30 ± 0.16		
75.83		23.39 ± 0.12	

[a] Hours after 24.00 November 1995 UT.

for the 1993 SC star, the scatter was 0.04. These scatters are slightly less than the quoted uncertainties for the TNO magnitudes, showing that the quoted TNO magnitude uncertainties are reasonable.

3. RESULTS

3.1. 1994 TB

The TNO 1994 TB was discovered by Jewitt and Chen (1994) on R band CCD images obtained from the University of Hawaii 2.2-m telescope. From R band images and an assumed albedo of 0.04, Jewitt and Luu (1995) have estimated the diameter of 1994 TB to be 306 km. Such a diameter is 13% the diameter of Pluto. Marsden (1995) has *assumed* that 1994 TB is in a Pluto-like orbit (2:3 Neptune resonance). An object in such an orbit has avoided perturbations by Neptune.

In Table I, we present our B, V, and R magnitudes for 1994 TB and the corresponding UT times. Simply averaging all data from each night yields the following nightly colors: night 1: V–R = 0.96; night 2: V–R = 0.64; B–V = 1.10; night 3: V–R = 0.53; night 4: V–R = 0.72; B–V = 0.91. The average V–R equals 0.71, with a scatter of 0.18 mag, while the average B–V is 1.00, with a scatter of 0.13 mag. The scatter in V–R colors is substantially larger than expected from the uncertainties in the measured magnitudes. A plot of magnitude vs time for 1994 TB and a field star of similar brightness to 1994 TB shows evidence for 1994 TB magnitude variations on a time scale of hours, naturally explained by rotational modulation. We experimented with fitting the magnitude–time points to simple sine curves. A sine curve with period of 3.44 hr and a total range of 0.34 mag appears to give a reasonable fit, for the small number of points we have. The average scatter of the measured magnitudes around these curves are well within the quoted uncertainties. We fit all 3 colors to the same curve, simply varying the mean magnitude to get the lowest deviation from the curve in each passband. The curves yield colors of V–R = 0.68, B–V = 1.10. The uncertainty in the V–R color from the curve fit is substantially less than that of the scatter from the average of the nightly means. The means derived in the two ways are similar. Thus, we believe we see a real rotational modulation in the magnitudes of 1994 TB, but our mean color does not depend on the exact details of the rotational modulation. The B–V color derived from the lightcurve fitting is 0.1 mag redder than the average of the two measurements. This is because these two measurements were obtained during the bright part of the light curve—the mean B magnitude is fainter. Because the lightcurve is very preliminary, it is not possible to assign precise errors on the colors. Clearly, however, the scatter from the light curve is comparable to the uncertainties in the individual magnitude measurements, so we adopt V–R = 0.68 ± 0.06 and B–V = 1.10 ± 0.15 for 1994 TB.

3.2. 1993 SC

The TNO 1993 SC was discovered by Williams *et al.* (1995) on R band CCD images obtained with the 2.5-m Isaac Newton Telescope. They have combined their R = 21.5 measurement and an assumed geometric albedo of 0.04 and found a diameter of 320 km for 1993 SC. As in the case of 1994 TB, Williams *et al.* have suggested 1993 SC may have existed in a Pluto-like orbit over the lifetime of the solar system.

In Table II, we present our B, V, and R magnitudes for 1993 SC and the corresponding UT times. Our nightly average colors for 1993 SC are: night 1: V–R = 0.70; night 2: V–R = 0.65; B–V = 1.35; night 3: V–R = 0.70; B–V = 1.19; night 4: V–R = 0.74. The average V–R is 0.70 with a scatter of 0.04 mag. The average B–V is 1.27,

TABLE II
BVR Magnitudes for 1993 SC

UT[a]	B	V	R
04.92		22.76 ± 0.06	
05.48			22.06 ± 0.06
28.55			22.10 ± 0.06
29.22		22.75 ± 0.06	
29.95	24.10 ± 0.15		
52.83	23.92 ± 0.15		
53.58		22.73 ± 0.06	
54.12			22.03 ± 0.06
76.62		22.72 ± 0.10	
77.32			22.02 ± 0.08
77.90			21.94 ± 0.06

[a] Hours after 24.00 November 1995 UT.

with a scatter of 0.11 mag. Because we see no evidence for rotational modulation (see discussion below) we adopt these average colors as our final colors for 1993 SC.

Comparison of our data with those of Williams *et al.* yield two apparent discrepancies. (1) A superficial comparison of our R magnitudes with those of Williams *et al.* yields a difference of 0.5 magnitudes, with Williams quoting an average R of 21.5, while we find an average R of 22.03. (2) Williams *et al.* find evidence for a rotational modulation with a 7.7129 hr period, while we find no evidence for significant variations.

A detailed comparison of our R magnitudes for 1993 SC with those of Williams *et al.* must take into account several factors: the different heliocentric and geocentric distances of the TNO, phase angle effects, and rotational modulation effects. We can carry out a detailed comparison in the following manner. The Williams *et al.* observations were obtained at $\alpha = 0.0°$, $\Delta = 32.9$ AU, and $r = 33.9$ AU. During our observations, $\alpha = 1.4°$, $\Delta = 33.7$ AU, and $r = 34.2$ AU. The differing distances lead to a magnitude difference of 0.08 mag with our observations fainter. If we use the Bowell "H,G" formalism (see Bowell *et al.* 1989 and Jewitt and Luu 1995) adopted by the IAU, with $G = 0.15$ for TNOs, the differing phase angles yield a magnitude difference of 0.20 mag, with ours fainter. The combination of distance and phase effects predicts that our magnitudes should be 0.28 fainter than those of Williams *et al.*, accounting for nearly 60% of the apparent discrepancy.

The effect of rotational modulation in comparing ours and Williams *et al.* R magnitude is harder to determine. We were not aware of the provisional period determined by Williams *et al.* when we were observing. Unfortunately, our observations were obtained with a time interval between observations equal to about 3.0 cycles of the 7.7129 hr period proposed by Williams *et al.* Thus, the fact that our R magnitudes show no sign of rotational modulation may just be a consequence of our observing interval. If we assume that our observations were obtained when 1993 SC was in the faint part of its lightcurve, then our magnitudes should be compared to the faintest Williams *et al.* magnitude (R = 21.9). Correcting our observed R of 22.03 to the distance and phase angle at the time of Williams *et al.* measurements yields R = 21.75. Given the uncertainties in period, amplitude, and phase corrections, the agreement between our observations and those of Williams *et al.* is quite good. Our data show no evidence of rotational modulation, but, because of the unfortunate observation intervals, they cannot be used to either confirm or reject the Williams *et al.* period. Further observations specifically designed to find rotational modulation are desirable since Williams *et al.* have stated that there is a statistical probability of 80% that their period is just random noise.

4. DISCUSSION

B–V and V–R colors allow us to place constraints on the surface composition of outer solar system bodies. For example, we can distinguish between surfaces dominated by icy, primitive, carbonaceous chondrite-like material and radiation damaged icy material.

Carbonaceous chondrites contain magnetite (Fe_3O_4), poorly crystallized graphite, fine-grained clay minerals such as montmorillonite ($Al_2Si_4O_{10}(OH)_2$), organic polymers, and iron sulfide. The most primitive carbonaceous chondrites can contain 8 to 22% H_2O chemically bound in minerals. Complex organic molecules compose ≤1% of a carbonaceous chondrite. Lebofsky (1978, 1981) has chemically tied carbonaceous chondrites to asteroids in the main belt. Specifically, he has found evidence of montmorillonite clay minerals and chemically bound H_2O in the spectra of the C-type asteroid 1 Ceres. C-type asteroids show solar B–V and V–R colors. Hartmann *et al.* (1990) have suggested that the solar-colored Centaur object 2060 Chiron (a recent refugee from the Kuiper Belt on an unstable Saturn crossing orbit) and the Saturnian satellite S9 Phoebe are objects with a mixture of volatile ices and C-class carbonaceous soil.

Laboratory experiments using KeV to MeV particle accelerators that simulate solar wind and cosmic ray bombardment of pure icy cometary surfaces have indicated that particle bombardment of cometary surfaces likely produced important structural and chemical changes to depths of several meters (Moore *et al.* 1983; Strazzulla *et al.* 1984;

TABLE III
Broad-Band Colors for TNOs, Centaurs, and Satellites

Object	B–V	V–R	Ref.
1994 TB	1.10 ± 0.15	0.68 ± 0.06	*a*
1993 SC	1.27 ± 0.11	0.70 ± 0.04	*a*
1993 SC	0.92 ± 0.11	0.57 ± 0.09	*b*
1992 QB_1	0.65 ± 0.10	0.60 ± 0.10	*b*
1993 FW		0.40 ± 0.10	*b*
1993 HA2	0.88 ± 0.07	0.72 ± 0.05	*b*
5145 Pholus	1.19 ± 0.10	0.78 ± 0.05	*a*
5145 Pholus	1.35 ± 0.10	0.71 ± 0.05	*c*
2060 Chiron	0.67 ± 0.06	0.34 ± 0.03	*b*
S9 Phoebe	0.70	0.46	*d*
Pluto	0.867		*e*
Charon	0.700		*e*
Triton	0.72	0.38	*d*
Sun	0.67	0.36	*f*

[a] This work.
[b] Luu and Jewitt 1996.
[c] Mueller *et al.* 1992.
[d] Degewij *et al.* 1980.
[e] Binzel 1988.
[f] Hartmann *et al.* 1990.

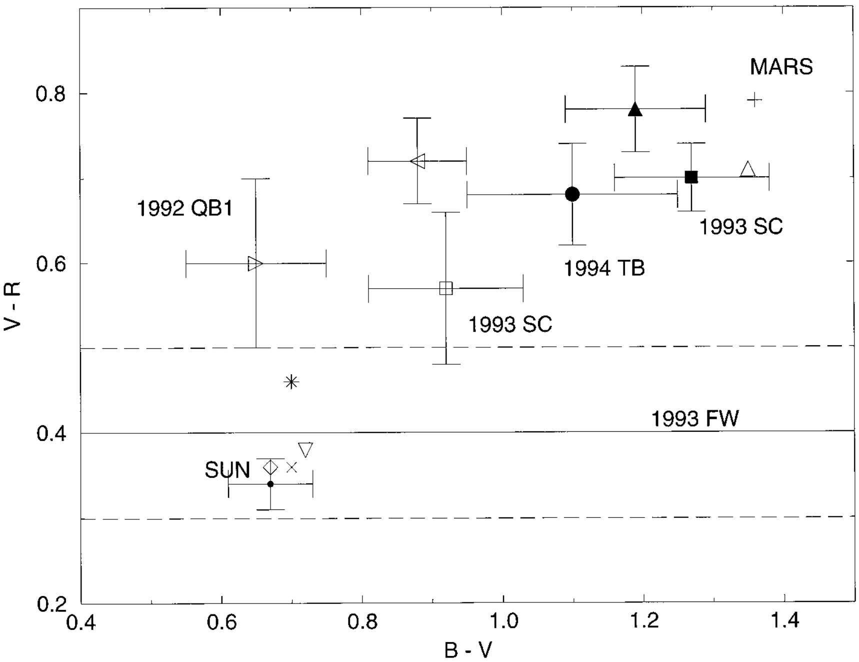

FIG. 1. A color–color plot of outer solar system objects. (1994TB—filled circle; 1993SC this work—filled square; 1993SC from Jewitt and Luu—open square; 1992 QB1—open right triangle; 1993 FW—solid line and uncertainties are designated by dashed lines; 1993 HA2—open left triangle; 5145 Pholus this work—filled upward triangle; 5145 Pholus from Mueller *et al.*—open upward triangle; Mars—plus; S9 Phoebe—star; Triton—open downward triangle; Charon—X; 2060 Chiron—dot; Sun—open diamond). Redder objects are toward the upper right hand corner and bluer objects are toward the lower left hand corner. Mars and the Sun have been plotted for reference. The TNOs 1994 TB and 1993 SC are almost as red as 5145 Pholus.

Johnson *et al.* 1984, 1985, 1987; see also Mumma *et al.* 1993). In particular, the experiments have indicated that particle bombardment likely synthesized new organic solids (rich in CH_3, CH_2, $C{=}O$, and $C{=}C$ groups) and caused surface darkening and color changes (reddening). Mueller *et al.* (1992) suggested that the red color of Centaur object 5145 Pholus arises from a concentration of solid organic substances of greater purity than that found on other solar system bodies, such as C-class asteroids, where dark, neutral-colored carbon materials dominate. Mueller *et al.* have suggested that the red coloring agent may be similar to the irradiated CH_4 ice residue of Strazzulla *et al.* In addition, Sawyer *et al.* (1987) have suggested that the redder color of Pluto (B–V = 0.867) arises from complex organic molecules produced from the photolysis of CH_4 ice. In the same manner the solar color of Charon (B–V = 0.700) arises because of the significantly lower abundance of CH_4 ice on the surface of Charon and therefore the much lower abundance of complex organic molecules on the surface.

In Table III we have compared TNO colors with outer solar system objects and in Fig. 1 we have plotted the objects on a color–color diagram. In the diagram the reddest objects are toward the upper right hand corner and the bluest objects are toward the lower left hand corner. Mars and the Sun have been plotted for reference. Our measurements show that 1994 TB and 1993 SC are among the reddest objects in the solar system. However, Luu and Jewitt (1996) have obtained a low signal-to-noise spectrum of 1993 SC and have concluded that there is nothing unusual about the color of 1993 SC (see Fig. 1 for a comparison of our colors and the Luu and Jewitt colors for 1993 SC).

Is there evidence for a diversity of TNO surface colors? The evidence for color diversity is certainly tantalizing, but not yet firm. We have found colors for 1994 TB and 1993 SC that are very red and consistent with surfaces rich in complex organic molecules, but inconsistent with carbonaceous chondrite like soil. At the other extreme, Luu and Jewitt (1996) have found 1993 FW nearly solar in color. Colors are needed for many more TNOs before we can say with certainty that diversity exists. In addition, the intrinsic observational challenge of obtaining colors for these faint objects necessitates confirmation measurements by independent groups.

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