

BVR PHOTOMETRY OF CENTAUR OBJECTS 1995 GO, 1993 HA₂, AND 5145 PHOLUS

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ABSTRACT

We present *B*, *V*, and *R* band photometry for three of the six known Centaur objects. We have measured *V*–*R* colors of 0.47 ± 0.04 and 0.77 ± 0.05 for the Centaurs 1995 GO and 1993 HA₂, respectively, as well as a *B*–*V* color of 0.75 ± 0.04 for 1995 GO. We have measured *B*–*V* and *V*–*R* colors for the Centaur 5145 Pholus that closely agree with previous measurements in the literature. We have found that the four Centaurs with known colors can be separated into two groups, one group with near solar colors (2060 Chiron and 1995 GO) and the other with very red colors (5145 Pholus and 1993 HA₂). Centaurs with solar colors may have surfaces rich in icy, primitive, carbonaceous chondrite like material while Centaurs that have very red surfaces may have icy surfaces rich in complex carbon bearing molecules. The differences in the surfaces of Centaurs may result from differences in their primordial composition. Perhaps, 5145 Pholus and 1993 HA₂ had higher initial concentrations of simple ice components (e.g., CH₄) than 2060 Chiron and 1995 GO that upon cosmic ray or solar wind bombardment produced larger amounts of red colored complex organic molecules. Alternatively, Centaurs may have originated with similar initial compositions and thermal processing and coma formation may have altered the surface composition and hence the color of Centaurs closer to the Sun, 1995 GO (perihelion distance, $q = 6.85$ AU) and 2060 Chiron ($q = 8.45$ AU), but not the composition and hence the red color of Centaurs farther from the Sun, 5145 Pholus ($q = 8.68$ AU) and 1993 HA₂ ($q = 11.83$ AU). © 1997 American Astronomical Society. [S0004-6256(97)00505-0]

1. INTRODUCTION

Kowal *et al.* (1979) discovered the first member (2060 Chiron) of a new class of solar system objects (now known as Centaurs), more remote than asteroids, but larger than normal comets. Kowal *et al.* and Kowal (1989) have found that 2060 Chiron is on a Saturn crossing orbit with a perihelion distance of 8.45 AU and an aphelion distance of 18.96 AU, just inside the orbit of Uranus. Dynamical studies have suggested that 2060 Chiron is evolving from the outer to the inner solar system toward an orbit resembling that of a short period comet (Scholl 1979). In addition, Duncan *et al.* (1988) have carried out numerical simulations that suggest 2060 Chiron originated in the Kuiper Belt. Meech & Belton (1989, 1990) reported the first detection of a coma about 2060 Chiron and Bus *et al.* (1991) have reported the detection of the CN (3880Å) emission band, the characteristic signature of a cometary coma, in spectra of 2060 Chiron. Near infrared spectra of 2060 Chiron show no evidence of absorption bands associated with solid organic material (Luu *et al.* 1994). Campins

et al. (1994) have calculated the diameter of 2060 Chiron at 180 km.

Rabinowitz and the Spacewatch Telescope on Kitt Peak discovered the next Centaur object (5145 Pholus; Scotti 1992). Marsden (1992) has found that 5145 Pholus is on a Saturn and Neptune crossing orbit with a perihelion distance of 8.68 AU and an aphelion distance of 31.96 AU. Deep CCD images have shown no evidence of a coma (Hainaut & Smette 1992). Measurements of *B*–*V* = 1.35, *V*–*R* = 0.71, and *R*–*I* = 0.72 (Mueller *et al.* 1992) and *V*–*R* = 0.81 (Buie & Bus 1992) have indicated that 5145 Pholus is redder than any known asteroid or comet. CCD spectra have shown no evidence for cometary emission bands or mineralogical absorption bands (Fink *et al.* 1992). Near infrared spectra of 5145 Pholus have shown evidence for the presence of solid organics (Davies *et al.* 1993).

Six objects are now classified as Centaurs (2060 Chiron, 5145 Pholus, 1993 HA₂, 1994 TA, 1995 DW₂, and 1995 GO; see Weissman & Levison 1996). In addition, Hartmann *et al.* (1990) have suggested that S9 Phoebe (an outer retrograde satellite of Saturn) may be a captured Centaur object.

S9 Phoebe and 2060 Chiron have similar sizes and broad band colors as well as interactions with Saturn. It is now widely believed that Centaur objects originated in the Kuiper Belt (see Weissman & Levison 1996).

Almost nothing is known about the chemical nature of the Centaurs that have been discovered so far. Even the most basic questions remain unanswered. Do Centaurs show a similarity or a diversity in their surface compositions? If a diversity exists does it result from (a) inhomogeneities in the primordial solar nebula or (b) greater thermal processing and possible coma formation for Centaurs closer to the Sun? It is possible that Centaurs have surfaces that are dominated by (a) pure H₂O ice (similar to Pluto's moon Charon), (b) carbonaceous chondritic like material or, (c) a mixture of ice components similar to that of short period comets (frozen H₂O, CO, CH₃OH, CO₂, NH₃, CH₄, HCN, and silicates) but richer in complex organic molecules as a result of cosmic ray and solar wind bombardment of their surfaces.

We have initiated a program to constrain the surface composition of Centaurs. The faintness of the Centaurs (other than 2060 Chiron and 5145 Pholus) has prevented us from carrying out visible or infrared spectroscopic observations. However, we have carried out *B*, *V*, and *R* photometry for the Centaurs 1993 HA₂ and 1995 GO. Our measurements allow us to place some of the first constraints on the surface compositions of 1993 HA₂ and 1995 GO.

2. OBSERVATIONS

Observations were obtained of the Centaurs 1993 HA₂ and 1995 GO as well as the standard star field in M67 (Schild 1983) and a Landolt (1992) standard star field (PG 1633+099) on a photometric night, 1996 April 14 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. Observations reported here of Pholus were obtained during a run in 1995 November, using the same equipment (Tegler & Romanishin 1997).

The initial CCD reductions were fairly standard, using a combination of twilight and dark sky observations for flat-fielding. After bias subtraction and flatfielding, the regions around the Centaurs and standard stars 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.

Aperture photometry was done with the PHOT task in the IRAF DIGIPHOT package. An aperture of 8 arcsec diameter (12 pixel radius) was used for the standard stars and the relatively bright object Pholus. Given the typical seeing (1.5 arcsec FWHM) this aperture encompassed essentially all the light from stellar objects. For the fainter objects 1995 GO and 1993 HA₂, we measured the objects in a 8 pixel radius aperture, and determined aperture corrections for each individual frame by measuring several field stars in small and

large apertures. For the relatively nearby object 1995 GO, motion during the exposures resulted in trailed images. We took this into account by comparing GO to images of artificially trailed field stars, as discussed in more detail below. The sky value was found in an annulus from 15 to 20 pixel 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.

For both April and November runs, transformation equations were derived from the stars in the M67 field and one or two Landolt (1992) fields containing 4 or more stars spanning a range of colors. In April, we used the PG 1633+099 Landolt field, while in November we used the PG 0231+051 and PG 2213-006 fields. The color transformations appear to be accurate to the 0.01 mag level, while the *V* zero point appears accurate to the 0.02 mag level.

3. RESULTS

3.1 1993 HA₂

Rabinowitz discovered the Centaur 1993 HA₂ with the 0.9-m Spacewatch Telescope on Kitt Peak (Marsden 1993). Rabinowitz reported discovery *V* magnitudes that ranged from 20.0 to 20.5 over four days. Marsden (1996) has reported that 1993 HA₂ has a perihelion distance outside the orbit of Saturn at 11.82 AU, an aphelion distance outside the orbit of Neptune at 37.65 AU, and an eccentricity of 0.522.

We have measured a *V* band magnitude of 20.84 ± 0.04 and a *V*−*R* color of 0.77 ± 0.05 from two *V* images and two *R* images of 1993 HA₂, each image with a five minute integration time. Our *V* magnitude for 1993 HA₂ is in good agreement with the *V* magnitude given by the online ephemeris program of the International Astronomical Union (*V* = 20.8). Also, our *V*−*R* color for 1993 HA₂ is in agreement with the color of Luu & Jewitt (1996), *V*−*R* = 0.72 ± 0.05 .

3.2 1995 GO

The Centaur 1995 GO was discovered by Scotti and Jedicke with the Spacewatch Telescope on Kitt Peak (Marsden 1995). The discovery *V* magnitudes ranged from 20.0 to 21.0 over 13 days. Marsden (1996) has reported that 1995 GO has a perihelion distance inside the orbit of Saturn at 6.85 AU, an aphelion distance inside the orbit of Neptune at 29.39 AU, and an eccentricity of 0.622.

For 1995 GO, we have three 10 min and four 5 min exposures in *R*, one 10 min and four 5 min exposures in *V*, and three 5 min exposures in *B*, spread over a 3 hour period. On both the 5 and 10 min exposures, the image of GO was noticeable trailed due to the motion of the object. To take this into account in doing the photometry, we did the following. The motion of GO (about 0.54 pixel per min) was found from measuring the objects position relative to field stars on the earliest and latest images. Each image was then artificially trailed so that the star images had the same shapes as the trailed image of GO. The instrumental magnitudes of GO were measured on the original images, before the artificial

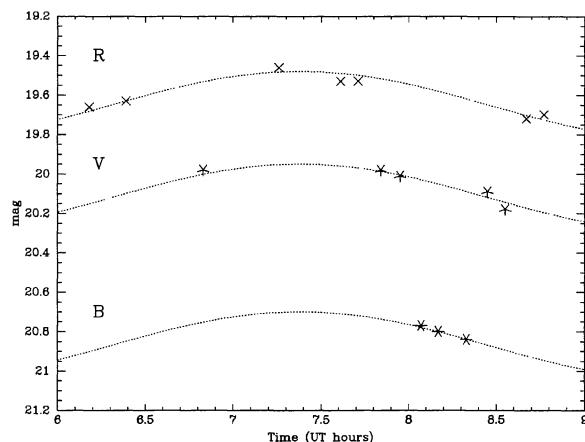


FIG. 1. The magnitudes of 1995 GO in R , V , and B bandpasses vs time measured in hours from 1996 April 13.00 UT. As discussed in the text, the dotted curve is a sine curve with a period of 4.3 hours used to tie together the magnitudes in the different colors. The curves for all bandpasses are identical, except for a shift corresponding to $V-R=0.47$ and $B-V=0.75$.

trailing, and 3 field stars were measured with the same aperture on the artificially trailed images. The standard magnitudes of the 3 field stars were found from instrumental magnitudes measured on the original images. The magnitudes differences between GO and each field star was found by comparing the magnitudes of the (artificially) trailed star images and the observed trailed GO image, and the final magnitudes of GO found from these differences and the derived magnitudes of the field stars.

The magnitudes (shown in Fig. 1) show clear evidence for light variations, presumably caused by rotational modulation effects. Our data do not span a long enough time period to make a meaningful measurement of period or amplitude. To measure accurate colors, however, we have to take the variations into account, so we fit, by trial and error, a sine curve to the seven R mag vs time points. The curve shown in Fig. 1 is a sine with period of 4.3 hours and a total amplitude of 0.34 mag. This curve was then shifted in magnitude only to provide the best fit to the V and B points. The shifted curve fit the V and B points nicely, with a scatter around the curve of 0.03 in V and 0.01 in B . We stress that we have not found a measure of the period of 1995 GO— the curve used is only used as a numerical “French curve” to allow us to tie together the observations in the different filters.

The colors derived from the curve shifts are: $V-R=0.47\pm0.04$, and $B-V=0.75\pm0.04$. Once again our V magnitude measurement is in good agreement with the V magnitude generated by the online ephemeris program of the International Astronomical Union ($V=19.9$). We have carried out a thorough search of the literature and have found no colors for 1995 GO.

3.3 5145 Pholus

We obtained three 5 minute exposures of 5145 Pholus through each of B , V , and R filters during a 1 hour long period centered at 11:41 UT on 1995 November 27. We have measured $V=18.46\pm0.05$, $B-V=1.19\pm0.10$, and $V-R=0.78\pm0.04$. Our color measurements are in good

agreement with those of Mueller *et al.* 1992 and Buie & Bus (1992). Our V magnitudes are also in good agreement with those of Mueller *et al.* 1992 and Buie & Bus (1992), after we take into account differences in heliocentric and geocentric distances and phase angles in the 3 sets of observations.

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 rich in complex organic molecules.

Carbonaceous chondrites contain magnetite (Fe_3O_4), poorly crystallized graphite, fine-grained clay minerals like montmorillonite ($\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$), 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 $\leq 1\%$ of a carbonaceous chondrite. Lebofsky (1978, 1981) has chemically tied carbonaceous chondrites to asteroids in the 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 2060 Chiron and 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; 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) has suggested that the red color of 5145 Pholus arises from a concentration of solid organic substances of greater purity than that found on other solar system bodies, like C-class asteroids, where dark, neutral-colored carbon materials dominate. Mueller *et al.* have suggested 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 1 and Fig. 2 we have compared the colors of 1993 HA₂ and 1995 GO with the colors of Trojan asteroids, other Centaurs, and Trans-Neptunian Objects (TNOs) observed by our group (Tegler & Romanishin 1997) and other groups. In Fig. 2 the reddest objects are toward the upper right hand corner and the bluest objects are toward the lower

TABLE 1. Comet nucleus, Trojan asteroid, Centaur, and TNO colors.

Object	$B-V$	$V-R$	Perihelion (AU)	Ref
Sun	0.67	0.36		
P/Encke		0.48 ± 0.02	0.33	a
P/Halley		0.43 ± 0.03	0.60	a
P/Arend-Rigaux		0.53 ± 0.03	1.39	a
P/Tempel 2		0.58 ± 0.03	1.48	a
P/Neujmin 1		0.52 ± 0.04	1.55	a
1583 Antiochus	0.76	0.42	5.10	b
1437 Diomedes	0.71	0.37	5.13	b
624 Hektor	0.77	0.44	5.20	b
659 Nestor	0.75	0.40	5.22	b
1208 Troilus	0.73	0.32	5.22	b
617 Patroclus	0.68	0.33	5.23	b
1173 Anchises	0.70	0.32	5.33	b
1995 GO	0.75 ± 0.04	0.47 ± 0.04	6.85	c
2060 Chiron	0.67 ± 0.06	0.34 ± 0.03	8.45	d
5145 Pholus	1.19 ± 0.10	0.78 ± 0.04	8.68	c
5145 Pholus	1.35 ± 0.10	0.71 ± 0.06		e
5145 Pholus		0.81 ± 0.01		f
1993 HA ₂		0.77 ± 0.05	11.83	c
1993 HA ₂	0.88 ± 0.07	0.72 ± 0.05		d
1994 TB	1.10 ± 0.15	0.68 ± 0.06	27.05	g
1993 SC	1.27 ± 0.11	0.70 ± 0.04	32.19	g
1993 SC	0.92 ± 0.11	0.57 ± 0.09		d
1992 QB ₁	0.65 ± 0.10	0.60 ± 0.10	40.88	d
1993 FW		0.40 ± 0.10	41.56	d

a: Jewitt 1991; b: Degewij & Van Houten 1979; c: This work; d: Luu & Jewitt 1996; e: Mueller *et al.* 1992; f: Buie & Bus 1992; g: Tegler & Romanishin 1997.

left hand corner. The objects observed by our group have filled symbols and those observed by other groups have open symbols. Mars and the Sun have been plotted for reference. At first glance, Fig. 2 has the appearance of a scatter plot. Hence, a superficial examination of Fig. 2 indicates that there may be a diversity of TNO and Centaur colors and hence a diversity of surface compositions. From Table 1 and Fig. 2 we see that the observations of 1993 SC, 1993 HA₂, and 1992 QB₁ by Luu & Jewitt (1996) play a central role in the color diversity as they link the near solar colored objects to the very red objects. Our sample and the Luu & Jewitt sample overlap in that we both have measurements of $B-V$ and $V-R$ colors for 1993 SC and $V-R$ colors for 1993 HA₂. Our color measurements for 1993 SC are significantly different from those of Luu & Jewitt (see Fig. 2). Specifically, Jewitt & Luu have concluded that there is nothing to distinguish the colors of 1993 SC from colors of known asteroids and comet nuclei. Our results on the other hand have suggested that the colors of 1993 SC are as red as 5145 Pholus and are therefore very different from known comet nuclei and asteroids. Although our $V-R$ color for 1993 HA₂ agrees within the uncertainties with that of Luu & Jewitt, our measurements indicate that 1993 HA₂ is an extremely red object. Our observations appear to weaken the case for a diversity of colors among TNOs. Although a diversity of colors for TNOs is possible, we remain open to the possibility that Centaurs show a diversity of colors, but the

vast majority of TNOs are very red. Clearly, colors are needed for many more TNOs and Centaurs.

Two fundamental questions remained unanswered because published $B-V$ and $V-R$ colors exist for only eight TNOs and Centaurs. (a) Do the vast majority of TNOs have red surfaces? (b) What mechanism is responsible for the different colors of Centaurs (and possibly TNOs)?

Perhaps the differences among Centaur (and possibly TNO) surfaces are primordial. Formation mechanisms may have produced a composition gradient in the Kuiper Belt, much like that which exists in the asteroid belt. Perhaps, the red Centaurs and TNOs had primordial compositions enriched in ice components (e.g., CH₄) that upon cosmic ray and solar wind bombardment produced complex organic molecules with a red color. Perhaps the solar colored Centaurs and TNOs had primordial compositions depleted in ice components such as CH₄. Only one TNO has a solar colored surface. Luu & Jewitt (1996) have reported that 1993 FW has $V-R=0.4 \pm 0.1$. Future observations should be aimed at verifying the solar color of 1993 FW as well as seeing if additional TNOs have solar colored surfaces.

Another mechanism that may be causing differences in surface colors among Centaurs is thermal in nature. Perhaps the vast majority of TNOs and Centaurs (with large perihelion distances) have primordial surfaces that have been enriched in complex organic molecules as a result of 4.5 billion years cosmic ray and solar wind bombardment. Perhaps Cen-

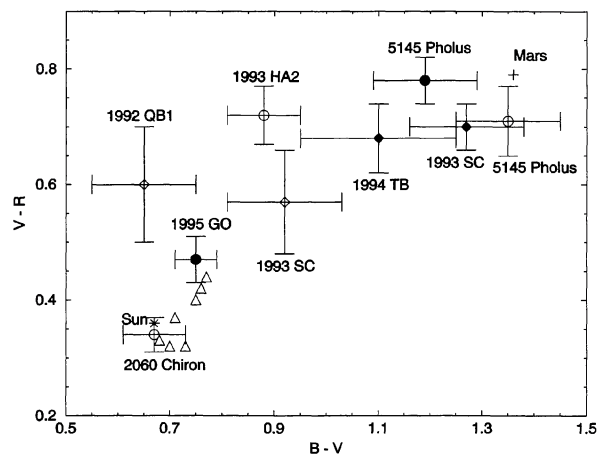


FIG. 2. A color-color plot of Trojan asteroids, Centaurs, and TNOs. Redder objects are toward the upper right hand corner and bluer objects are toward the lower left hand corner. Solid symbols are from Tegler & Romanishin (1997) and this paper. Open symbols are from the literature. Triangles, circles, and diamonds represent Trojan asteroids, Centaurs, and TNOs, respectively. The Sun and Mars are represented by a star and plus, respectively, and are shown for reference. The Centaur 1995 GO has colors similar to D-type Trojan asteroids. The Centaur 5145 Pholus and the TNOs 1994 TB and 1993 SC are among the reddest objects in the solar system and are therefore consistent with surfaces rich in complex organic molecules.

taurs with small perihelion distances have nearly solar colors. Specifically, Centaurs closer to the Sun may have undergone cometary activity (coma formation) that has covered the radiation processed mantle with fall back debris or thermally destroyed the red colored complex organic material. In Fig. 3, we have plotted the $V-R$ colors of comet nuclei, Centaurs, Trojan asteroids, and TNOs against their perihelion distances (see Table 1). Once again our observations have been represented by filled symbols and those of other groups by open symbols. With the exception of 1993 FW, the TNOs (1994 TB, 1993 SC, 1992 QB₁) and Centaurs (5145 Pholus and 1993 HA₂) in the outer solar system ($q > 8.45$ AU) show redder colors than Centaurs in the inner solar system (1995 GO and 2060 Chiron), comet nuclei, and Trojan asteroids. Future $B-V$ and $V-R$ measurements for the Centaurs 1995 DW2 ($q = 18.86$ AU) and 1994 TA ($q = 11.71$ AU) as well as additional TNOs are essential tests.

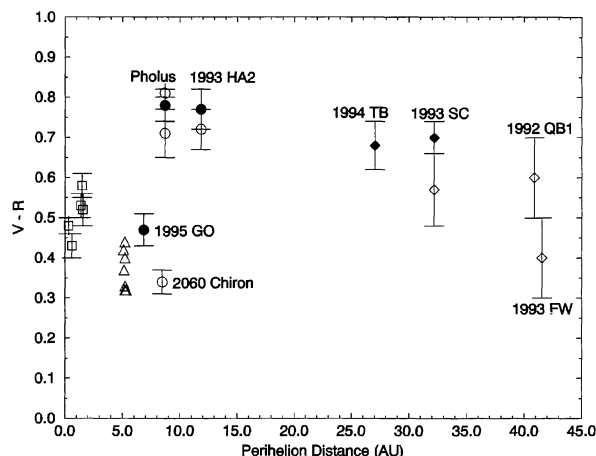


FIG. 3. A plot of comet nuclei, Trojan asteroids, Centaurs, and TNOs vs perihelion distance (Table 1). Squares, triangles, circles, and diamonds represent comet nuclei, Trojan asteroids, Centaurs, and TNOs, respectively. There is tentative evidence that Centaurs with larger perihelion distances (5145 Pholus and 1993 HA₂) have redder colors than Centaurs with smaller perihelion distances (2060 Chiron and 1995 GO), Trojan asteroids, and comet nuclei. Such a correlation (if verified) is consistent with coma formation resurfacing red cosmic ray processed surfaces with neutral colored interior material.

Luu & Jewitt (1996) have suggested that global resurfacing as a result of collisions may be responsible for color differences among Centaurs and TNOs. The impact of kilometer sized TNOs with hundred kilometer sized TNOs we have been observing may dredge up solar colored material buried beneath the radiation processed mantle of a TNO. Weissman & Stern (1994) have estimated that Charon has been bombarded by ~ 460 TNOs one kilometer in size during the 4.5 billion year lifetime of the solar system. Future light curve measurements in B , V , and R bands of Centaurs and TNOs will determine whether or not Centaurs and TNOs have color variations with longitude and latitude and thereby test the importance of collisional modification of TNOs and Centaur surfaces.

In summary, a great deal of observational work is necessary in order to characterize the chemical composition of Centaurs and TNOs and as well as the mechanisms that have modified the surfaces of Centaurs and TNOs.

REFERENCES

- Buie, M. W., & Bus, S. J. 1992, *Icarus*, 100, 288
 Bus, S. J., Schleicher, D. G., Bowell, E., & A'Hearn, M. F. 1991, *Science* 251, 774
 Campins, H., Telesco, C. M., Osip, D. J., Rieke, G. H., Rieke, M. J., & Schulz, B. 1994, *AJ*, 108, 2318
 Davies, J. K., Sykes, M. V., & Cruikshank, D. P. 1993, *Icarus*, 102, 166
 Degewij, J., & Van Houten, C. J. 1979, *Asteroids* (University of Arizona Press, Tucson), p. 417
 Duncan, M., Quinn, T., & Tremaine, S. 1988, *ApJ*, 328, L69
 Fink, U., Hoffmann, M., Grundy, W., Hicks, M., & Sears, W. 1992, *Icarus*, 97, 145
 Hainaut, O., & A. Smette 1992, *IAUC* 5449
 Hartmann, W. K., Tholen, D. J., Meech, K. J., & Cruikshank, D. P. 1990, *Icarus*, 83, 1
 Jewitt, D. 1991, *Comets in the Post-Halley Era* (Kluwer, Dordrecht), p. 19
 Johnson, R. E., Lanzerotti, L. J., & Brown, W. L. 1984, *Adv. Space Res.* 4, 41
 Johnson, R. E., Barton, L. A., Boring, J. W., Jessor, W. A., Brown, W. L., & Lanzerotti, L. J. 1985, in *Ices In The Solar System*, edited by J. Klinger, D. Benest, A. Dollfus, and R. Smoluchowski (Reidel, Dordrecht), p. 301
 Johnson, R. E., Cooper, J. F., Lanzerotti, L. J., & Strazzulla, G. 1987, *A&A*, 187, 889
 Kowal, C. T. 1989, *Icarus*, 77, 118
 Kowal, C. T., Liller, W., & Marsden, B. G. 1979, *Dynamics Of The Solar System, Proceedings Of The Symposium* (Reidel, Dordrecht), p. 245

- Landolt, A. U. 1992, *AJ*, 104, 340
Lebofsky, L. A. 1978, *MNRAS*, 182, 17
Lebofsky, L. A. 1981, *Icarus*, 48, 453
Luu, J., Jewitt, D., & Cloutis, E. 1994, *Icarus*, 109, 133
Luu, J. X., & Jewitt, D. C. 1996, *AJ*, 111, 499
Marsden, B. G. 1992, *IAUC*, 5480
Marsden, B. G. 1993, *IAUC*, 5789
Marsden, B. G. 1995, *MPEC* 1995-g12 (apr 10)
Marsden, B. G. 1996, <http://cfa-www.harvard.edu/cfa/ps/lists/centaurs.html>
Meech, K. J., & Belton, M. J. S. 1989, *IAUC*, 4770
Meech, K. J., & Belton, M. J. S. 1990, *AJ*, 100, 1323
Moore, M. H., Donn, B., Khanna, R., & A'Hearn, M. 1983, *Icarus*, 54, 388
Mueller, B. E. A., Tholen, D. J., Hartmann, W. K., & Cruikshank, D. P. 1992, *Icarus*, 97, 150
Mumma, M. J., Weissman, P. R., & Stern, S. A. 1993, *Protostars and Planets III* (University of Arizona Press, Tucson), pp. 1177–1252
Sandford, S. A., & Allamandola, L. J. 1988, *Icarus*, 76, 201
Sawyer, S. R., Barker, E. S., Cochran, A. L., & Cochran, W. D. 1987, *Science*, 238, 1560
Schild, R. E. 1983, *PASP*, 95, 1021
Scholl, H. 1979, *Icarus*, 40, 345
Scotti, J. V. 1992, *IAUC*, 5434
Strazzulla, G., Cataliott, R. S., Calcagno, L., & Foti, G. 1984, *A&A*, 133, 77
Tegler, S. C., & Romanishin, W., 1997, *Icarus* (in press)
Weissman, P. R., & Levison, H. F. 1996, *Pluto-Charon* (University of Arizona Press, Tucson)
Weissman, P. R., & Stern, S. A. 1994, *Icarus*, 111, 378