Physical Characteristics of Trans-Neptunian Objects and Centaurs.

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Abstract. The available knowledge of the sizes, rotation periods, lightcurve amplitudes, colours and spectra of the Centaurs and Trans-Neptunian Objects is summarised. There are a wide range of reflectances within the Centaur population and no obvious correlations with heliocentric distance. Spectroscopic evidence, including the detection of water ice, points to the Centaurs being large, inactive cometary nuclei. Published photometry of the Trans-Neptunian Objects is often inconsistent, but some conclusions are presented on the issues of spectral diversity within the Kuiper Belt and on the relationship between the Centaurs and the Trans-Neptunian Objects.

1 Introduction

Although no formal definition exists, the Centaurs may be regarded as a group of minor planets following unstable orbits with semi-major axes between those of Jupiter (5.2 AU) and Neptune (30 AU). Eight such objects are presently known. Canonically Centaurs have been identified as asteroids at discovery although (2060) Chiron was subsequently shown to have cometary activity. Jewitt and Kalas (1998) define Centaurs as having both perihelia and semi-major axes between Jupiter and Neptune by which definition the comets P/Oterma and P/Schwassmann-Wachmann 1 also qualify for inclusion. The Centaurs are believed to be in the process of diffusing inwards from dynamically chaotic regions within the large reservoir of planetesimals lying beyond Neptune (Morbidelli, Thomas and Moons 1995; Malhotra 1996). See also the earlier review by Stern and Campins 1996 and the discussion of the dynamical fate of Pholus-like objects in Asher and Steele 1993.

The Trans-Neptunian Objects, also known as Kuiper Belt Objects after Kuiper (1951) and Edgeworth-Kuiper Objects (Edgeworth 1943)[1], comprise three dynamical classes of more distant objects close to or beyond the orbit of Neptune. Objects in the 3:2 mean motion resonance with Neptune have been described as "Pluto Type" (Marsden 1996) or more commonly "Plutinos" (Jewitt and Luu 1996), those beyond about 41 AU as "Cubewanos" (Marsden 1997) or "Classical Kuiper Belt Objects", and those having a much larger semi-major axis and higher eccentricity than the Plutinos and Classical Kuiper Belt Objects

[1] For this review I have adopted the term Trans-Neptunian Object (TNO) in preference to KBO or EKO as this was the title proposed by the workshop Scientific Organising Committee and it is the least controversial of the possibilities.

are known as Scattered Disk Objects (Luu et al. 1997) . There is to date a single member known of this latter class (1996 TL_{66}) although it may be the harbinger of a much larger and more significant population.

2 Sizes

Since they are not resolved and their albedoes are generally unknown, sizes of these distant objects are best estimated via thermal models similar to those used for asteroids. These require simultaneous, or at least quasi-simultaneous, observations in both the visible and thermal (infrared or mm) regimes. Such observations have been done for the Centaurs Chiron (eg. Lebofsky et al. 1984; Sykes and Walker 1991; Campins et al. 1994; Altenhoff and Stumpff 1995;) Pholus (Howell et al. 1992; Davies et al. 1993a, 1996), and 1997 CU_{26} (Jewitt and Kalas 1998). In addition, Bus et al. (1996) used an occultation technique to place lower limits on the size of (2060) Chiron and these are in good agreement with the other results. The albedo deduced for (2060) Chiron is typically higher than for (5145) Pholus and 1997 CU_{26}, possibly because of resurfacing related to its cometary activity. However, since low albedoes are typical of short period cometary nuclei it has become conventional to assume an albedo of 0.04 for the Centaurs, leading to the remaining estimated diameters quoted in Table 1, which is modified from that presented by Jewitt and Kalas (1998).

Table 1. Orbital parameters and sizes for Centaurs

Name	q(AU)	Q(AU)	e	i (deg)	Diameter (km)	Albedo
(2060) Chiron	8.5	18.8	0.38	7	180±10	0.15±0.05
(5145) Pholus	8.7	31.8	0.57	25	190±22	0.04±0.03
(7066) Nessus	11.8	37.4	0.52	16	∼78	-
1994 TA	11.7	22	0.3	5	∼22	-
1996 DW_2	18.9	31	0.24	4	∼70	-
(8405) 1995 GO	6.9	29.3	0.62	18	∼74	-
1997 CU_{26}	13.1	18.4	0.17	23	302±30	0.045±0.010
1998 SG_{35}	6.8	11.0	0.23	12	∼18	-

Based on the number of detections in their medium depth ecliptic survey, Jewitt et al. (1996) suggested that there were of order 2600 Centaurs with diameters greater than 75km. Jedicke and Herron (1997) used the number of Centaurs detected by the Spacewatch automated search programme to estimate that there must be fewer than ∼2000 Centaurs, with only three of these having diameters greater than about 200km. With the discovery of (2060) Chiron, (5145) Pholus, and 1997 CU_{26}, all of which are close to or over this limit, it may be that these three have already been found.

Attempts to determine the sizes and albedos of TNOs using the Infrared Space Observatory ISO have only been partly successful (Thomas et al. 1999) but these observations tend to confirm the generally low albedos assumed for these objects.

3 Rotation Periods and Lightcurve Amplitudes

Knowledge of the synodic period of (2060) Chiron has been steadily improved by the work of *e.g.* Bus et al. (1989), Luu and Jewitt (1990) Dahlgren et al. (1991) and Marcialis and Buratti (1993). Luu and Jewitt (1990) and Meech and Belton (1990) explained the systematic changes in the amplitude of the lightcurve by the diluting effect of Chiron's coma.

Buie and Bus (1992) presented a lightcurve of (5145) Pholus and demonstrated convincingly a 9.9825±0.004 hour rotation period with an amplitude of ~0.15mag; Hoffmann et al. (1993) deduced a similar period and amplitude. Davies et al. (1998a) used the lightcurve parameters of Buie and Bus to fit 13 V magnitudes recorded over 3 days in 1998 and confirmed the 1992 result. Brown and Luu (1997) presented a complete lightcurve of (8405) 1995 GO and derived a period of 8.87±0.02 hours and an amplitude ~0.34mag. Davies et al. (1998a) combined these data with values from Romanishin et al. (1997) and new data from 1997 to argue for a slightly longer period and larger amplitude (~0.55mag). However, the quoted amplitude differences may reflect different philosophies, the Brown and Luu value being the amplitude produced by minimising the χ^2 value of a sine fit and the Davies et al. value being the actual peak to peak range of a curve which is not truly sinosodial. W. Brown (Private communication) reports that R band photometry of 1997 CU_{26} shows no variation within the likely errors over a period of 5 days, a result consistent with the limited visible photometry of Davies et al. (1998a) and the infrared measurements of McBride et al. (1999).

To date few TNO lightcurves have been published. Using the relatively small number of observations made at the time of its discovery, Williams et al. (1995) suggested a possible lightcurve amplitude of 0.5mag and period of 15hrs for 1993 SC. However, more comprehensive studies by Davies et al. (1997) and Tegler et al. (1997) placed upper limits of 0.1 and 0.06 respectively on this object's lightcurve and were unable to identify a rotation period. Luu and Jewitt (1998) reported that 1996 TL_{66} shows no evidence for rotational modulation greater than 0.05mag over a period of 6 hours. Similar results come from Delahodde et al. (1999) and Collander-Brown et al. (1999) which are consistent with the remark of Jewitt and Luu (1998) that "rotational modulation of the brightness is typically less than a few tenths of a magnitude although individual objects may of course exceed this". Romanishin and Tegler (1998) reported the absence of a detectable lightcurve in a number of the larger TNOs but suggested that 1994 TB, 1994 VK_8 and 1995 QY_9 have rotation rates of order 6-10 hours and amplitudes of 0.3-0.5mag. (See Table 2 and Fig. 1). By assuming that the lightcurve variations

Fig. 1. Lightcurve of 1995 QY_9 from Romanishin and Tegler (1998)

in the TNOs were due to irregular shapes, and then using the presumed strength of likely icy materials to determine the minimum size of objects likely to collapse into a sphere under self-gravity, Romanishin and Tegler (1998) went on to argue for TNOs having albedos close the range of 0.04 found for the Centaurs rather than the higher albedos of bodies such as Pluto and Triton.

4 Colours

4.1 Visible Colours

Visible (BVRI) colours for the Centaurs have been reported by Mueller et al. (1992), Luu and Jewitt (1996a), Green et al. (1997), Romanishin et al. (1997), Brown and Luu (1997), Tegler and Romanishin (1998), Magnusson et al. (1998) and Davies et al. (1998a). In general these are in good agreement but there are two exceptions. Brown and Luu determined a V$-$R color of 0.73$\pm$0.04 for (8405) 1995 GO which is significantly different from the value of 0.47$\pm$0.04 obtained the same month by Romanishin et al. (1997) and from the value of 0.41$\pm$0.02 found by Davies et al. (1998a) a year later. For 1995 DW_2 Luu and Jewitt

Table 2. Rotation periods and amplitudes

Name	Period (hrs)	Amplitude (Mag)	Reference
(2060) Chiron	5.9180 ± 0.0001	0.088 ± 0.003	Bus et al. (1989)
(2060) Chiron	5.91780 ± 0.00005	0.09-0.045	Luu and Jewitt (1990)
(2060) Chiron	$\sim$5.92	0.07 ± 0.02	Dahlgren et al (1991)
(2060) Chiron	5.917813 ± 0.000007	0.04	Marcialis and Buratti (1993)
(5145) Pholus	9.9825 ± 0.004	$\sim$0.15	Buie and Bus (1992)
(5145) Pholus	9.9768 ± 0.001	~ 0.2	Hoffmann et al. (1993)
(8405) 1995 GO	8.87 ± 0.02	0.34	Brown and Luu (1997)
(8405) 1995 GO	8.9351 ± 0.0003	$\sim$0.55	Davies et al. (1988)
1997 CU_{26}	?	Small	Brown (Pers Comm)
1998 SG_{35}	>12hr	>0.4	Green (Preliminary result)
1993 SC	?	< 0.1	Davies et al. (1997)
1993 SC	?	< 0.06	Tegler et al. (1997)
1994 TB	~ 6	~ 0.3	Romanishin and Tegler(1998)
1996 TL_{66}	?	< 0.1	Luu and Jewitt (1998)
1996 TO_{66}	?	< 0.1	Romanishin and Tegler(1998)
1996 TO_{66}	$\sim$6.25	$\sim$0.1	Delahodde et al. (1999)
1996 TP_{66}	?	< 0.07	Collander-Brown et al. (1999)
1994 VK_8	~ 10	$\sim$0.4	Romanishin and Tegler (1998)
1994 VK_8	?	0.6	Collander-Brown et al. (1999)
1995 QY_9	~ 8	$\sim$0.6	Romanishin and Tegler (1998)

(1996a), Green et al. (1997), Tegler and Romanishin (1998) and Magnusson et al. (1998) all give rather different BVRI colours which are not consistent within their quoted errors. In the case of 1995 GO the redder values of V-R seem incompatible with the visible-infrared colours reported elsewhere and so I have adopted the lower values. In the case of 1995 DW_2, which is presently much fainter than (8405) 1995 GO, an average value is used. The representative mean colours are given in Table 3.

To date, there has been no evidence of colour variations with rotational phase in any of the well observed Centaurs which eliminates surface hetrogeneity on hemispherical scales as a likely explanation for the observed differences in colours reported by different observers.

4.2 Visible-Infrared Colours

Visible-Infrared, basically V-JHK, colours were shown by Hartmann et al. (1982) to be useful in probing the surface compositions of minor planets and comets.

Ideally, to derive visible-IR colours, data over the whole range of wavelengths would be obtained quasi-simultaneously as was done for (2060) Chiron in 1988 (Hartmann *et al.* 1990). However in reality visible and infrared observations tend to be significantly non-simultaneous and most attempts to derive visible-IR colors for Centaurs (*e.g.* Hartmann et al. (1982), Davies et al. (1992,1993b, 1996,1998a); Weintraub et al. (1997)) have used V magnitudes estimated using the object's absolute magnitude H_V and assumed values of the phase curve slope parameter G. A fundamental weakness of this approach is that it cannot take account of lightcurve variations unless the lightcurve is known with high precision and the interval between the lightcurve determination and the photometric observations is short enough that the uncertainties in the period cannot build up significantly. These effects may be negligible in the case of the larger Trans-Neptunian Objects, for which no significant lightcurves have yet been detected, but must be considered when dealing with smaller, and potentially irregular objects. In these cases it may be uncertainties in rotational phase, rather than photometric precision, which dominate the uncertainty in the colours.

Combining all the data produces the visible-IR colours given in Table 3 and the reflectivity curves plotted in figure 2. The unusual 'Cometary asteroid' 1996 PW is included in Table 3 for comparison. Note that while Davies et al. (1998b) and Hicks et al. (1999) argue on colour grounds that this is a quiescent comet nucleus, Weissman et al. (1998) suggest that it is an asteroid like object returning to the inner solar system after a soujourn in the Oort cloud.

Table 3. Visible–Infrared Colours of Centaurs

Object	B−V	V−R	V−I	V−J	V−H	V−K	Notes
(2060) Chiron		0.37±0.03	0.72±0.04	0.9–1.5	1.2-1.8	1.4–1.8	Variable
(5145) Pholus	1.27±0.1	0.78±0.03	1.55±0.02	2.59±0.02	2.96±0.02	2.93±0.02	
(8405) 1995 GO	0.75±0.04	0.44±0.03	0.96±0.03	1.65±0.02	2.02±0.06	2.11±0.05	V-R of 0.73 not used
(7066) Nessus	1.09±0.04	0.79±0.04	1.50±0.10	2.29±0.04	2.57±0.1	2.57±0.1	
1997 CU_{26}	0.77±0.05	0.47±0.02	1.01±0.02	1.74±0.02	2.15±0.02	2.22±0.03	
1995 DW_2	0.54±0.1	0.43±0.07	0.92±0.1	1.31±0.1	–	–	
1996PW	–	0.56±0.04	1.03±0.06	1.80±0.05	2.19±0.05	–2.23±0.05	Comet-like orbit

4.3 TNO Visible Colours

Luu and Jewitt (1996a), Green et al. (1997), Tegler and Romanishin (1997), Jewitt and Luu (1998) and Magnusson et al. (1998) present visible colours which

Fig. 2. Reflectivity curves for Centaurs as given by McBride et al. (1999).

show a wide range of values amongst the TNO population and they argue for significant colour diversity in the TNO population. Barucci et al. (1999) confirm this result. However, Tegler and Romanishin (1998) suggest on the basis of BVR colours, which they believe are more accurate than those of earlier workers, that these distant objects comprise two populations, with one group of objects being only slightly redder than the Sun (Chiron like) while the others are very red indeed (Pholus like). That such differences in photometry can exist is clear when comparing the BVRI data from several groups as is done in Table 4. In some cases, for example 1996 TP_{66} and 1996 TO_{66} the V−R colours are in good agreement, in others both the V−R, and particularly the B−V, are not consistent within the quoted photometric errors. This phenomenon was also pointed out by Tholen (1998) and Barucci et al. (1999) who showed that the level of inconsistency far exceeds that expected from the errors quoted by the different groups.

Several factors may be contributing to this effect. Davies et al. (1997) emphasized the difficulties involved in photometry of faint moving objects and show, based on reduction of 33 frames of the Kuiper Belt object 1993 SC using different techniques, that the statistical uncertainties of most photometric software packages provide an underestimate of the true observational errors, indeed they obtained significantly different values for the V magnitude of 1993 SC using different reduction techniques on the same frames. It may be significant that almost all of the groups cited in Table 4 appear to have used different filter sets including Mould BVRI, Harris BVR, Kitt Peak VRI and Bessell BVRI. Interestingly the B-V colours of the best observed TNOs derived using the University of Hawaii 88 inch telescope are consistently bluer (ie B-V is numerically smaller) than those obtained at other telescopes. This may be indicative of different responses of various filter/CCD combinations which may make intercomparison of data from different groups more difficult than might first be assumed.

4.4 TNO Visible-Infrared Colours

Jewitt and Luu (1998) extended the issue of colour diversity by presenting V-JHK colours for 5 TNOs. They found a range of V-JHK similar to that amongst the Centaur population and a strong relationship of V-J to M_R with the redder objects being associated with fainter absolute magnitudes (See Fig. 3). If one assumes a roughly constant albedo amongst objects of different colours, this implies the smaller objects are redder. This colour-size relationship would be consistent with the retention of surface frosts, which are generally blue in colour, by the larger objects. However it is worth noting that even the largest objects in this sample are much smaller than Pluto and Triton which are known to have at least partly icy surfaces. Davies et al. (1997) and Davies et al. (in prep) independently confirm several of these the V-J values although their failure to detect at J some other objects which ought to have been detectable according to the V-J vs M_R relationship, suggests that this relationship may not hold for all TNOs. Luu and Jewitt (1996) and Barucci et al. (1999) find no correlation of V-R with H_V in a somewhat larger sample of objects. Jewitt and Luu (1998) speculate that the failure to detect such a relationship in their earlier data may be because BVRI does not give a long enough baseline for the effect to become apparent, because the other objects were on average smaller or because the apparent correlation is in fact a fluke.

5 Spectroscopy

5.1 The Centaurs

The visible spectra of the 6 brightest Centaurs are featureless (Binzel 1992,1997, Lazzarin and Barucci 1998), with slopes ranging from flat (2060) Chiron, 1995 DW_2) to red ((5145) Pholus, (7066) Nessus) as would be expected from their visible colours. Fink et al. (1992) and Binzel (1992) suggested refractory organic materials (tholins) to explain the steep red slope of Pholus and Hoffmann et al. (1993) interpreted the data with more detailed models of tholins plus dark but spectrally neutral material.

Luu et al. (1994) reported that (2060) Chiron has a featureless infrared spectrum similar to many C type asteroids, as did M. Brown (1998) who obtained

Table 4. Visible colours of TNOs by different groups

Object	B−V	V−R	V−I	Reference	Notes
1993 SC	0.92 ±0.11	0.57 ±0.09	1.43±0.15	Luu and Jewitt (1996)	Colours from spectra
1993 SC	0.94 ±0.05	0.68 ±0.04	1.36±0.04	Jewitt and Luu (1998)	
1993 SC	1.27 ±0.11	0.70 ±0.04		Tegler and Romanishin (1998)	
1993 SC		0.54 ±0.14	0.97±0.14	Davies et al. (1997)	V may be unreliable
1994 TB	1.10 ±0.08	0.74 ±0.11		Barucci et al. (1999)	
1994 TB	0.88 ±0.15	0.85 ±0.15	1.5±0.25	Luu and Jewitt (1996)	
1994 TB	1.10 ±0.15	0.68 ±0.06		Tegler and Romanishin (1998)	
1994 TB		0.69 ±0.07	1.46±0.10	McBride (*Priv Comm*)	
1996 TL_{66}	0.74 ±0.08	0.46 ±0.05	0.72±0.07	Barucci et al. (1999)	
1996 TL_{66}	0.58 ±0.05	0.13 ±0.06	0.67±0.05	Jewitt and Luu (1998)	
1996 TL_{66}	0.75 ±0.02	0.35 ±0.01		Tegler and Romanishin (1998)	
1996 TL_{66}		0.36 ±0.04		McBride (*Priv Comm)*	
1996 TO_{66}	0.72 ±0.07	0.34 ±0.04	0.76±0.04	Barucci et al. (1999)	
1996 TO_{66}	0.59 ±0.04	0.32 ±0.06	0.68±0.05	Jewitt and Luu (1998)	
1996 TO_{66}	0.74 ±0.03	0.38 ±0.03		Tegler and Romanishin (1998)	
1996 TO_{66}		0.39 ±0.03	0.73±0.03	McBride (*Priv Comm*)	
1996 TO_{66}	0.58 ±0.06	0.42 ±0.07		Delahodde et al. (1999)	
1996 TP_{66}	1.14 ±0.14	0.65 ±0.13	1.08±0.14	Barucci et al. (1999)	
1996 TP_{66}	0.80 ±0.07	0.65 ±0.07	1.36±0.06	Jewitt and Luu (1998)	
1996 TP_{66}	1.17 ±0.05	0.68 ±0.03		Tegler and Romanishin (1998)	
1996 TP_{66}		0.68 ±0.04	1.01±0.03	McBride (*Priv Comm*)	

a similar result for for (8405) 1995 GO. R. Brown et al. (1998) presented a 1.4-2.2μm spectrum of 1997 CU_{26} which shows a red spectral slope and absorptions at 1.52 and 2.03 μm indicative of water ice, but no other identifiable spectral features. A similar result was reported by M.Brown and Koresko (1998). The general shape of the near infrared spectrum of 1997 CU_{26} was confirmed by McBride et al. (1999).

Infrared spectroscopy of (5145) Pholus revealed a unique spectral feature at a wavelength of about 2.25 μm (Davies et al. 1993) which Wilson et al. (1994) proposed might be explained by a mixture of a specific tholin, HCN polymer

Fig. 3. The V-J vs M_R relationship for 5 TNOs noted by Jewitt and Luu (1998).

plus H_2O and NH_3 ices. Luu et al. (1994) obtained higher quality IR spectra of (5145) Pholus and noted the similarity of the spectrum to a laboratory tar sand. Recently Cruikshank et al. (1998) have combined much of the available spectroscopy and photometry of (5145) Pholus and fit this with a model containing a red refractory organic material (tholin), frozen methanol or a photolytic product of that molecule, water ice, olivine and carbon. On this basis they argue that (5145) Pholus is a very primitive object akin to a cometary nucleus which has never been active. The IR spectrum of (5145) Pholus remains unique, observations of a variety of low albedo asteroids such as those in the Cybele, Hilda and Trojans by Luu et al. (1994) and Dumas et al. (1998) have failed to find an object with a similar 2 μm feature. Noll and Luu (1998) and McCarthy et al. (1998) report programmes to obtain additional spectroscopic data for Centaurs and TNOs using NICMOS on the Hubble Space Telescope.

5.2 The Trans-Neptunian Objects

The first visible spectrum of a Trans-Neptunian Object was presented by Luu and Jewitt (1996b) who reported a reddish slope indistinguishable from many asteroids and comet nuclei and noted that the slope was intermediate between those of Centaurs (2060) Chiron and (5145) Pholus. They noted that their spectrum was not well represented by a linear fit and remarked that this might reflect absorption or emission features in the spectrum. Brown et al. (1997) presented a 1.4-2.2μm spectrum of 1993 SC which had a strongly red continuum and spectral features similar to those seen on Pluto and Triton. On the basis of these features Brown et al. argued for the presence of simple hydrocarbons such as CH_4, C_2H_6, C_2H_4 or C_2H_2 on the surface of 1993 SC. However the slope of the Brown et al. spectrum is not consistent (being too red) with the H-K colours of Jewitt and Luu (1998), a disagreement which is troubling. Luu and Jewitt (1998) present an almost continuous spectrum of 1996 TL_{66} between 0.4 and 2.2 μm which is flat and featureless, showing none of the absorption features typical of those of pure ices.

6 Discussion

It does seem clear that the surface colors of the Centaur objects cover a wide range which is representative of objects in the Kuiper Belt. This is consistent with, although does not uniquely demonstrate, that Centaurs are escaped Trans-Neptunian Objects. However is not clear to what extent the properties of the Centaurs can be extrapolated to interpret observations of the Trans-Neptunian Objects. For example, the V-J vs M_R relationship seen in 5 Trans-Neptunian Objects by Jewitt and Luu (1998) is not reflected amongst the presently known Centaurs, although this may not be surprising since the Centaurs have already had different evolutionary histories to the TNOs. Weintraub et al. (1997) suggested that there might be a trend of decreased reddening with reducing semi-major axis amongst the Centaurs and explained this in terms of increased exposure to the Sun since leaving the Trans-Neptunian region. However this relationship is not supported by the larger dataset of Centaur colours and spectra now available.

The activity of (2060) Chiron, which is not confined to periods around perihelion but occurs sporadically through its entire orbit (Bus et al 1998) has undoubtedly affected its surface colours. (Note that Chiron was paradoxically quiet close to its recent perihelion passage (eg Lazarro et al 1996, 1998)). While no such activity has been seen for other Centaurs, given the short observational baselines to date, similar sporadic activity cannot be discounted. It also appears that the standard JHK broad band filters may not be very helpful in distiguishing the spectral characteristics of Centaurs and TNOs since they are too broad to resolve specific absorption bands from water and methane ices. In this respect it can be noted that (8405) 1995 GO and 1997 CU_{26} have almost identical V-JHK colours yet one shows ice absorptions in its spectrum and the other does not.

When presenting their data suggesting bi-modality in the BVR colours, Tegler and Romanishin (1998) failed to find any correlation of BVR colour with a number of parameters including semi-major axis, inclination or absolute magnitude and did not advance a specific model to explain thier observations. Luu and Jewitt (1996a) developed a model in which the colour of the TNOs is determined by a balance between cosmic ray induced reddening of a surface dominated by ices and impact induced resurfacing. They suggested that impacts penetrate the irradiation crust and eject material which is less red and less dark than the ancient surface. Since the present observational data refers to colours averaged over a hemisphere, unless one process is dramatically faster than the other this will naturally produce a range of colours. Given the ubiquity of cosmic radiation so far from the Sun and the evidence that large TNOs should have surfaces which have been extensively reworked by impact cratering (Durda et al. 1999) this seems a reasonable explanation of the observations. However at the present time it is impossible to distinguish between a diverse population containing "families" of intrinsically different composition and a weathered or impact gardened population.

In many respects there is an analogy between the present situation of TNO research and that of the early classification of main belt asteroids into a small number of groups based on UBV observations. Only when considerable extra data were available for a larger number of objects was the true structure and complexity of the main belt understood. The same is almost certainly true of the Trans-Neptunian region.

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