

COLOUR PROPERTIES AND TRENDS IN TRANS-NEPTUNIAN OBJECTS

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Abstract. One of the most puzzling features of the Kuiper Belt, which has been confirmed by numerous surveys, is the optical colour diversity that seems to prevail among the observed TNOs. TNOs and Centaurs have surfaces showing dramatically different colours and spectral reflectances, from neutral to very red. With the relatively few visible-NIR colour datasets available, the colour diversity seems also to extend to the near infrared wavelengths. Relevant statistical analyses have been performed and several studies have pointed out strong correlations between optical colours and some orbital parameters (i , e , q) for the Classical Kuiper Belt objects. On the other hand, no clear trend is obvious for Plutinos, Scattered objects or Centaurs. Another important result is the absence of correlation of colours with size or heliocentric distance for any of the populations of outer Solar System objects. The strong colour anisotropy found is important because it is a diagnostic of some physical effects processing the surfaces of TNOs and/or some possible composition diversity. In this paper, we will review the current knowledge of the colour properties of TNOs, describe the observed colour distribution within the Edgeworth–Kuiper belt, and address the problem of their possible origin.

1. Introduction

The trans-Neptunian objects (TNOs) make up a recently discovered class of objects populating the outer edges of the Solar System. They presumably contain the most pristine material observable from earth. This is a new and very fast evolving branch of planetary science. In this paper, we will review the latest results obtained on multicolour photometry, mainly from the Meudon Multicolour Survey (2MS) that sample a *large, unique* and *homogeneous* colour dataset for 52 Centaurs and trans-Neptunian objects.

Since the discovery of the first TNO, a decade ago, numerous investigations have been performed regarding dynamical questions as well as physical properties. They have dramatically increased the knowledge of the outer solar system and have led to many surprises. One of them is that the Kuiper belt objects are highly non-uniformly distributed in objects falling in three usually distinguished populations. The **Resonant objects** are trapped with mean motion resonances with Neptune. They have orbits with large eccentricities and inclinations. Most of them are known as Plutinos (little Plutos) for their dynamical similarity with Pluto (2:3 resonance). Few objects are also trapped in other resonances like the 3:4, 3:5, 1:2. The less



excited **Classical TNOs** populate the region between the 2:3 (39.4 AU) and the 1:2 resonance (47.7 AU). Finally, the **scattered disk** contains objects with very large and eccentric orbits beyond $a = 48$ AU. They are potentially encountering close interaction with Neptune and may play a significant role in understanding the transfer rate and evolution in other important classes of outer solar system objects: the Centaurs and the comets.

Another main surprise is the large diversity in the colours of the objects (see Barucci et al., 2001 and references therein). Colours vary from slightly blue to very red. Since it is believed that the TNOs were formed more or less at the same time and in the same cold region of the outer solar system, this important colour variation may be mainly due to different degrees of surface evolution.

Since the discovery of 1992 QB₁, the existence of TNOs immediately raised questions about their physical nature. As these bodies are indeed likely to be remnant planetesimals from the early solar system, any information on their physical and compositional properties is cosmologically very relevant. However, characterization of the entire population is required and for the moment only multicolour broadband photometry allows a compositional survey relevant for statistical work. For such photometric surveys the immediate goals are:

- To look for correlations between surface colours and physical and dynamical properties. Such correlations, if any, are likely to help understand the formation and evolution processes that affected the outer solar system.
- To search for interrelations between related populations such as Centaurs, short period comets or irregular satellites. The obvious goal is to search for a genetic link between these populations and help understand the transition paths between populations.
- Colour variation is another important issue as it may address whether or not the surfaces of TNOs are homogeneous.
- Finally, the ultimate goal for a colour analysis of a large number of TNOs would be to derive a taxonomy, as for the asteroids. It takes decades to achieve such a goal for asteroids, and it seems not easy to reach it for TNOs. However, some preliminary analyses have been done (Fulchignoni et al., 2004).

2. Observational Strategy

Because of their specific and unique nature, observation of trans-Neptunian objects requires adapted observational procedure and data reduction techniques, otherwise one may encounter systematic and devastating errors in the determination of the object magnitude. The faintness of these objects coupled with their slow proper motion and their self-rotation make TNOs challenging objects to those seeking to measure, for example, colours and light-curves. Indeed, the trans-Neptunian population represents some of the faintest objects in the Solar System. The typ-

ical apparent visual magnitude of a TNO is fainter than 23, though a few objects brighter than 22 have been found.

Data reduction requires also special treatment. The brightness of the object is measured through an aperture correction technique (Howell, 1989) as justified by the faintness of the TNOs. The basis of this method is that the photometric measurement is performed by using a small aperture of the order of the size of the seeing disk. Consequently, the uncertainty in the measurement is reduced because less noise from the sky background is included in the aperture. Then, to determine how much light is thrown away, the so-called “aperture effect” is calibrated using a large number of nearby field stars. This is reasonable as the motion of TNOs during each exposure is smaller than the seeing, and hence the TNOs’ point spread functions (PSFs) are comparable to those of field stars. The advantages in the use of a small aperture are (i) to decrease the contribution of the sky which could be important and critical for faint objects, (ii) to minimize the probability of contamination from unseen background sources.

Several photometric surveys have led to the establishment of many interesting trends and correlations that we will summarize and discuss below. Among these surveys we will present the analysis that we have done on a large sample of 52 BVRI colours (The 2MS, Meudon Multicolour Survey). These colours have been obtained mostly at the 3.6-m Canada–France–Hawaii telescope. It is important to note that this 52 colours sample (described in detail in Doressoundiram et al. (2001, 2002)) makes up a large and homogeneous dataset (same team, same observation strategy and data reduction techniques), which has not been the case for most TNOs colours’ analyses that used compilations of different datasets. Obviously, with a homogeneous dataset, one can prevent possible inconsistencies between colour measurements of the same object from multiple investigators; the reasons for these possible inconsistencies being mainly different observation strategies, filter transformations and/or data processing methods.

3. Colour Diversity

Colour-colour plots display the differences in the reflectivity of the objects as compared to the Sun. Figure 1 shows the B-V versus V-R colours of the various dynamical classes of the TNOs (i.e., Classical objects, Plutinos, Scattered disk objects) and of the Centaurs. This plot shows that a wide colour diversity characterizes the outer solar system objects. TNOs have surfaces showing dramatically different colours and spectral reflectances, from neutral to very red. Moreover, all sub-classes are colour undistinguishable, which is consistent with a common origin of these objects. This colour diversity is also seen in the other colour-colour representations (i.e., B-V vs. R-I and V-R vs. R-I). Visible colours are mutually correlated (see Table I). Moreover Mc Bride et al. (2003) found that their V-J colours broadly correlated with published optical colours, thus suggesting that a

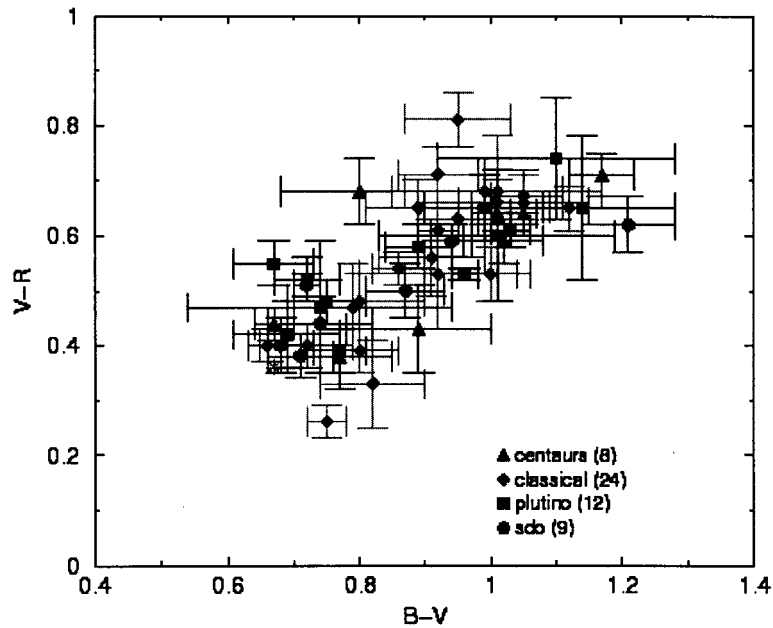


Figure 1. B-V versus V-R plot of the trans-Neptunian objects. The different classes of TNOs are represented: Plutinos, Classicals, and Scattered. The star represents the colours of the Sun. From Doressoundiram et al. (2002).

single colouring agent is responsible for the reddening from the B ($0.4 \mu\text{m}$) to the J ($1.2 \mu\text{m}$) regime. This remarkable property may help identify the agent among the low-albedo minerals with similar colours (Jewitt and Luu, 2001). The lower correlation between B-V and R-I results from the fact that the spectrum of the reddest objects generally flattens toward the infrared. This seems in agreement with the hypothesis that the surfaces of TNOs possess an irradiated icy crust. Indeed, according to the laboratory work of Thompson et al. (1987) on irradiated frosts, the reddest TNOs are expected to have a spectrum that flattens towards the infrared.

4. Comparison with Related Populations

It is believed that Centaurs and Short Period Comets (SPCs) populations are subsets of the TNO population, i.e., that SPCs are fragments of TNOs. If this hypothesis is valid, then it might be expected that the SPCs and TNOs should have the same gross compositions and one should search for genetic links in the colour distribution of those populations. Figure 2 is a colour-colour diagram of data on cometary nuclei (data from the colour compilation of Lamy et al. (2004)) compared to the TNOs and Centaurs data. Cometary nuclei data are scarce due to the difficulty of observing inactive small cometary nuclei at large heliocentric distances. Although all TNOs, Centaurs and SPCs populations are assumed to be made of the same primordial

TABLE I
Correlations found in the Meudon multicolour survey dataset

Quantity ¹	Quantity ¹	Group ²	r_{corr} ³	$P(r > r_{\text{corr}})$ ⁴	Significance ⁵	Other surveys
B-V	V-R	All (N = 52)	0.79	5×10^{-12}	$>8\sigma$	a, b
B-V	R-I	All (N = 51)	0.47	0.0006	3.4σ	a, b
V-R	R-I	All (N = 51)	0.47	0.0006	3.4σ	a, b
B-R	e	Classical (N = 22)	-0.60	0.003	3.0σ	a
B-R	i	Classical (N = 22)	-0.72	0.0002	3.8σ	a, c, e
B-R	q	Classical (N = 22)	0.76	4×10^{-5}	4.1σ	a, e, h
B-R	V_{rms}	Classical (N = 22)	-0.77	3×10^{-5}	4.2σ	a, d, h
Other correlations reported						
H	i	Classical (N = 80)				f
V-J	B-V	All (N = 27)	0.87			g
V-J	V-R	All (N = 27)	0.87			g
H	colors	Classical (N = 48)	Positive			a
H	colors	Plutinos (N=20)	Negative			a

¹ e = eccentricity, i = inclination, q = perihelion, V_{rms} = mean excitation velocity, H absolute magnitude.

²Dynamical class of TNOs and number of measurements in the sample.

³Spearman's rank correlation statistic.

⁴Significance of the correlation, assuming Gaussian statistics. 99.7% confidence level means a 3.0σ significance which is the nominal criterion for a statistically significant correlation.

References: a – Hainaut and Delsanti (2002), b – Jewitt and Luu (2001), c – Trujillo and Brown (2002), d – Stem (2002), e – Tegler and Romanishin (2000), f – Levison and Stem (2001), g – Mc Bride et al (2003), h – Boehnhardt et al (2002).

material, care must be taken when looking at interrelations between them. Because of observational biases, we are not looking at the same size distributions. Therefore, if resurfacing mechanisms are size dependant then comparison between the different populations may be misleading.

Having this fact in mind, when looking at the Figure 1, it is clear that TNOs and Centaurs seem to have similar broadband colours and this is consistent with a common origin. At optical wavelengths, the colours of the observed population of Centaurs and trans-Neptunian objects are quite diverse, ranging from solar colour ($B-V = 0.67$) to extremely red ($B-V = 1.2$). As opposed to the Centaurs, the colour distribution of cometary nuclei does not seem to match those of TNOs (Figure 2). The very red colour seems to be absent among comets, which is in contradiction with an origin within the Kuiper belt. Obviously, more data will be necessary to draw firm conclusions.

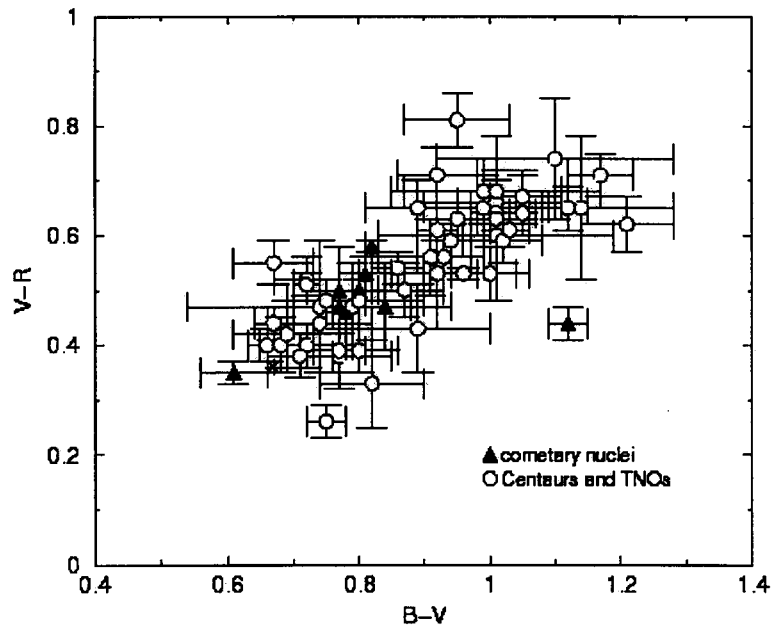


Figure 2. B-V versus V-R colour plot of TNOs (same as Figure 1) and Centaurs compared to the colours of cometary nuclei (Green et al., 1997; Lamy et al., 1999, 2001; Luu, 1993) populations.

5. Correlations with Surface Properties

Figure 3 and 4 display colours of TNOs and Centaurs (52 objects) in the orbital eccentricity versus semi-major axis plane and orbital inclination versus semi-major axis plane respectively. The symbols' sizes are proportional to the corresponding object's diameter. A colour palette has been adopted to scale the colour spread from $B-R = 1.01$ (coded as dark blue) to $B-R = 1.88$ (coded as red). As a comparison, $B-R = 1.03$ for the Sun and 1.97 for the Centaur 5145 Pholus (the reddest known object in the Solar System). 2:3 ($a \sim 39.5$ AU) and 1:2 ($a \sim 48$ AU) resonances with Neptune are shown, as well as the $q = 40$ AU perihelion curve. The advantage of this representation is that it offers to the eye the global colour distribution of the TNOs. Interesting patterns clearly emerge from this colour map. For instance, objects with perihelion distances around and beyond 40 AU are mostly very red (first shown by Tegler and Romanishin, 2000). Classical objects (between the 2:3 and 1:2 resonances) with high eccentricity and inclination are preferentially neutral/slightly red. Moreover, there is seemingly a red colour-low inclination cluster of TNOs. In contrast, no clear trend is obvious for Scattered TNOs ($a > 50$ UA), nor for the Plutinos, which appear to lack any trends in their surface colours.

These trends are interesting but need to be validated through robust statistical tools. With the increasing observational data, several authors performed statistical analyses and found significant trends (see Table I). I will give the results obtained

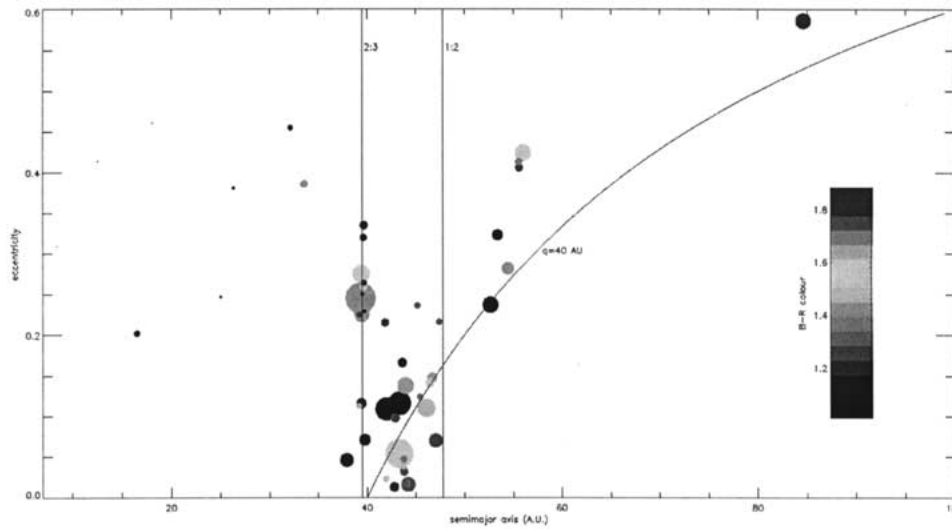


Figure 3. Colours of Centaurs and TNOs (52 objects) in the orbital eccentricity versus semi major axis plane. The size of the symbols is proportional to the corresponding object's diameter. Colours are scaled from blue (grey objects) to red (very red objects). 2:3 ($a \sim 39.5$ AU) and 1:2 ($a \sim 48$ AU) resonances with Neptune are marked as well as the $q = 40$ AU perihelion curve.

from the study of Doressoundiram et al. (2001, 2002) where the authors used a large and homogeneous dataset of 52 BVRI colours.

First of all there are the strong structures found for the Classical objects. Originally, Tegler and Romanishin (2000) found on a dataset of 32 objects a red colour

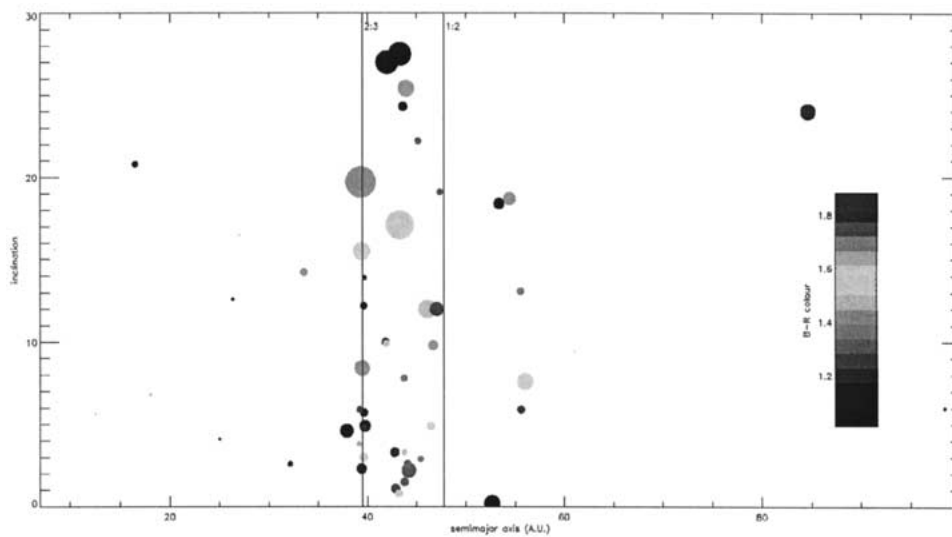


Figure 4. Same as Figure 5 in the orbital inclination versus semi major axis plane.

cluster at low i and Levison and Stern (2001) showed that low i Classical TNOs are smaller (greater H). Doressoundiram et al. (2001, 2002) found a strong and significant correlation between B-R colour and orbital inclination (see Table I). They found $r_{\text{corr}} = -0.72$ with a confidence level of 3.8σ . This result was also found by Trujillo and Brown (2002). We note that the correlation with B-V is stronger than with B-R, which in turn is stronger than with B-I ($r_{\text{corr}} = -0.69$). This is a result that is general to all the correlations found: the correlation is stronger at shorter colour wavelengths. This trend is a consequence of what was already noticed in colour-colour plots (Figures 1): most of the reddest TNOs have a spectrum that flattens toward the infrared. Another significant correlation exists also with orbital eccentricity ($r_{\text{corr}} = -0.60$ at the 3σ significance) though less strong than with i . This result was also established by Hainaut and Delsanti on a much larger dataset.

And finally, Doressoundiram et al. (2001, 2002) found a significant correlation with perihelion distance (q) for the Classical TNOs. Strikingly, Jewitt and Luu (2001) did not find any correlation with colour in their sample of 28 BVRI colour indices. This apparent discrepancy is most probably due to the high proportion of resonant objects included in their sample, which might have damped the correlation.

The most dynamically excited objects (high i and e) have the most neutral colours. Having this result in mind, several authors (Hainaut and Delsanti, 2002; Doressoundiram et al., 2001, 2002; Stern, 2002) have found a good correlation (Figure 5) between the colour index and $V_{\text{rms}} = V_k(e^2 + i^2)^{1/2}$ (V_k is the Keplerian orbital velocity given by $V_k = (29.8 \text{ km/s})a^{-1/2}$, and a is the semi-major axis expressed in Astronomical Units). V_{rms} is the mean excitation velocity. This parameter was used by the latter authors under the assumption that it is a good estimate of a given TNO's mean impact velocity. This correlation suggests, though does not prove (see next section), a possible role of collisions in colour anisotropies.

Considering that optical and infrared colours are correlated, one could presume that the correlations found between orbital parameters and optical colours can be generalized to infrared colours. Indeed, the V-J observations have a much wider spectral range and so, are likely to be more robust in showing colour correlations. However such statistical analysis is still tentative due to the relatively few V-J colours available. The first such attempt made by McBride et al. (2003) seems to support the colour and perihelion distance, and the colour and inclination relationships.

6. Origin of the Anisotropic Colour Distribution

The strong correlations found between colours and orbital parameters, underline the fact that colours are not randomly distributed within the trans-Neptunian objects, especially for the Classical TNOs between 40 and 48 AU. Both colour diversity and anisotropy have to be explained. Are they primordial? Or are

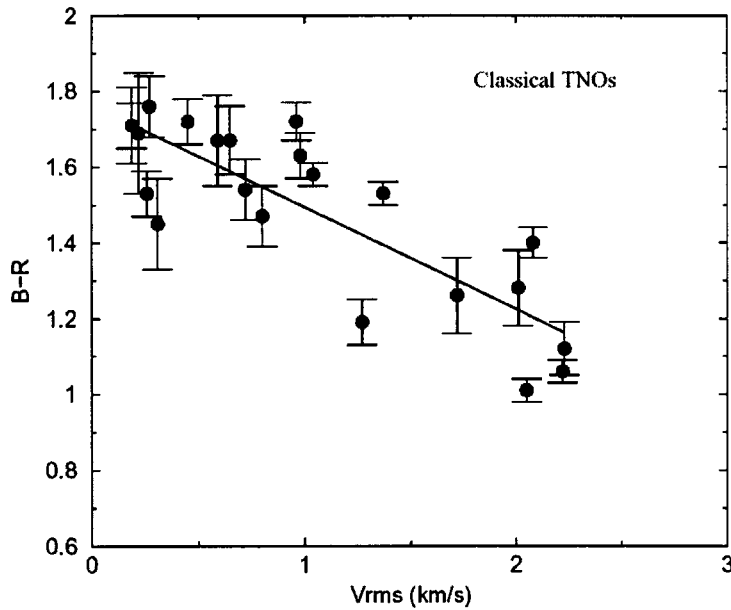


Figure 5. B-R color index versus mean excitation velocity plot of Classical objects, showing that $V_k(e^2 + i^2)^{1/2}$ is correlated with color. Spearman's rank correlation statistics gives $r_{\text{corr}} = -0.77$ (4.2σ significance). A linear least-squares fit has been plotted to illustrate the correlation. From Doressoundiram et al. (2002).

they the result of some evolutionary processes that modified TNO's surfaces and compositions during eons?

Several hypotheses have been suggested to explain the colour diversity. The immediate one is that the difference in colour reflects intrinsic compositional differences. However, the temperature difference between 30 to 50 AU (where the "classic" Kuiper Belt stands and is believed to have formed) is only 11 K, thus not enough to affect the composition of the TNOs. Because of this argument, this scenario is less favoured. However given the current uncertainties on the conditions and formation of the Kuiper Belt, this scenario cannot be definitively ruled out.

The collisional resurfacing (CR) hypothesis has been proposed by Luu and Jewitt (1996). It consists in the concomitant effect of two processes: radiation reddening and collision resurfacing blushing. Long term irradiation by energetic particles (space weathering) is known to cause surface darkening and reddening of the icy surfaces. The Collisional Resurfacing scenario supposes that mutual collisions among TNOs regularly excavate fresh neutral material to the objects surface and might counteract the competing space weathering reddening process. This scenario is merely a suggestion and quantitative modelling to check its validity is very difficult. Moreover, Luu and Jewitt (2001) rejected their initial hypothesis by pointing out that repeated determinations of colours taken at random rotational phases of TNOs are in agreement within the quoted measurement uncertainties

while colour differences among TNOs are much larger. However, we feel that present data are still poor to fully address the issue of colour/composition variation on the surface of TNOs. In this context, we can note a couple of on-going studies that investigate the variation of the surface composition with the rotation of the TNOs. For example, the spectroscopic study of Barucci et al. (2002) pointed out that the surface of the centaur 32532 (2001 PT13) did reveal two different behaviours with one showing the signature of water ice while the other no.

Another resurfacing process resulting from possible sporadic cometary activity has been suggested (Hainaut et al., 2000). Resurfacing by ice recondensation from a temporary atmosphere produced by intrinsic gas and dust activity might be an efficient process affecting the TNOs closest to the Sun (e.g., the Plutinos).

So, for the present time, the CR scenario seems to remain both a plausible explanation of the colour diversity and a natural origin mechanism for the colour – V_{rms} correlation found. In order to quantitatively check the validity of the CR scenario, Thébault and Doressoundiram (2003) and Thébault (2004) performed a numerical test. Indeed, V_{rms} gives only partial information on the collisional behaviour of a given TNO and modelling of the entire Kuiper disk collisional environment is required. They considered a target population of TNOs embedded in a swarm of small impactors distributed within the belt. Then, by following the dynamical collisional evolution of the TNOs, they estimated the relative spatial distribution of kinetic energy deposited on each object by collision. The conclusions of their study are as follow. The results do match several main statistical correlations found in the observed belt: e , i , V_{rms} and above all q *but* other features strongly contradict the observed correlations: (1) stronger correlation with e than with i ; (2) tendency towards highly impacted («bluer») plutinos. Those simulations show that the origin of the colour diversity is still unclear. The solution might lay in a better understanding of the physical processes at play, in particular the fact that the long-term effect of space weathering might significantly depart from continuous reddening (Moroz et al., 2004).

7. Investigation of a Possible Composition Diversity

In this section, we want to explore the possibility that the colour diversity may be the result of true compositional diversity. Tegler and Romanishin (2000) are so far the only investigators claiming for a colour bimodality. They saw in their colour dataset evidence that the TNOs' colours are divided into two distinct populations: one with solar like colours and one with red to very red colours. None of the other investigators could confirm this result and found a continuous colour dispersion rather than a colour bimodality. Doressoundiram et al. (2001, 2002) noted that this apparent paradox was not due to measurement mismatch. More data with small errors are needed to resolve this issue. However, if it is proven the colour bimodality cannot be explained by any evolutionary process. Indeed, such processes would

imply a continuous colour range. More striking is the presence of the red, low inclination cluster of Classical TNOs, reported by several observers (see Section 6). In fact, we note that the observed colour inclination correlation strongly relies on the presence of this cluster. Actually could the correlation be an artefact induced by the presence of the red-low i cluster? Should this be the case then explanations based on evolutionary mechanisms (like the CR scenario) would be ruled out in favor of a true composition difference and primordial distinct populations.

Levison and Stern (2001) have investigated this question and showed that the Classical objects might be the superposition of two distinct populations. The first population would contain dynamically hot objects with high inclination orbits and big objects. The second population would contain dynamically cold objects with low inclination orbits and relatively small TNOs. Independently, Brown (2001), analysing the unbiased inclination distribution of the Edgeworth–Kuiper belt, similarly concluded to a two-component inclination distribution of the Classical TNOs. Based on this bimodal behaviour of the Classical TNOs in both inclination and size, Levison and Stern (2001) speculated that the hot population (HP) originated from the inner regions of the disk where the size distribution and colour varied with heliocentric distance. On the other hand, the cold population (low i , $a > 41$ UA) should be primordial, and dynamically stable over the age of the Solar System, according to results of Duncan et al (1995). Members of this cold population (CP) should have very similar physical characteristics because they were formed at the same time and within a relatively narrow region. The existence of two distinct Classical populations appears to be borne out by the 2MS shown in Figure 4 where a red-low inclination cluster of TNOs is apparent.

In order to check that the two populations are statistically different regarding both their colours and sizes, Doressoundiram et al. (2002) applied a two-dimensional Kolmogorov–Smirnov (K–S) statistical test. They found that both CP and HP are two populations significantly different that could not be extracted from the same parent population.

If still speculative, this scenario is however opposite to the collision resurfacing hypothesis suggested by the V_{rms} correlation. In other words, the colour diversity could originate from true compositional diversity, and not from evolutionary processes reworking surfaces of TNOs. To test this hypothesis, Doressoundiram et al. (2002) analysed the colour-orbital excitation distribution within the HP. Surprisingly, they still found a 3.3σ ($N = 13$) strong and significant correlation between B-R colour and mean excitation velocity [$V_k(e^2 + i^2)^{1/2}$]. This result suggests that the dynamical excitation of TNOs' orbits probably plays a role in the colour diversity seen in the HP.

8. Discussion and Conclusions

With the large and high quality colour datasets available, strong and significant results have been found. Statistical analyses point to correlations between optical colours and some orbital parameters (i , e , q) for the Classical Kuiper Belt. On the other hand, no clear trend is obvious for Plutinos, Scattered objects or Centaurs, and no firm conclusions can be drawn regarding correlation of colours with size or heliocentric distance. The correlations of colour with i , e , and q are important because they may be the signatures of some physical processes altering the surfaces of TNOs. However, some contradictory results start to emerge at the Antofagasta meeting where new and large datasets obtained at ESO-VLT and HST make the picture of the obtained correlations less clear and less consistent. For instance, the VLT BVRI colour dataset (Boehnhardt et al., 2004) does not show as clear and as strong correlations as the correlations reported in this paper, while the HST VRI colour dataset (Stephens et al., 2004) did not confirm at all the correlations found for the Classical TNOs. In the case of the HST data, we suggest that the B wavelength may contain most of the redness information. Indeed, in the 2MS dataset, putting aside the B filter and including the I filter do weaken/remove all the correlations found. Also concerning the VLT data with less strong and obvious correlations, we have no answer at the present time. What we could see is that both the VLT dataset and the 2MS dataset are sampling different size distribution (the same applies also for the HST dataset)... This may reflect different surface processing whether one considers small or large objects. Further observational data will be necessary to establish the final word on this issue.

Instead of showing a continuous colour distribution from low inclined to high inclined orbits, the Classical objects may consist in the superposition of two (compositionally) distinct populations, as suggested by Levison and Stern (2001) and Brown (2001): a low i (dynamically Cold) population and a larger i (dynamically Hot) population. In particular, Levison and Stern found that low i classical TNOs are smaller (greater H). In addition, Tegler and Romanishin (2000) originally showed that low i classical TNOs are predominantly red. Doressoundiram et al. (2002) using a two dimensional Kolmogorov–Smirnov test found that the dynamically Cold Classical TNOs (red colours, low i , small sizes) and the dynamically Hot Classical TNOs (diverse colours, moderate and high i , larger sizes) are two populations significantly different that could not be extracted from the same parent population.

At present, no fully convincing mechanism exists that explains the anisotropic colour distribution within the Kuiper disk. We do not know whether the colour diversity is the result of true compositional diversity or whether it is the result of some evolutionary processes, as for example collisions. On the other hand, with the computational models performed so far coupled with the observational facts, we can conclude that collision alone cannot explain all, but it certainly plays a role in colour distribution seen at present time in the trans-Neptunian objects. Not

only collisions, but other evolutionary processes (i.e., outgassing, complex space weathering, ...) have also to be modelled. More observational data, numerical simulations, and overall laboratory experiments are required to unveil the origin of the colour properties and trends in the present Edgeworth–Kuiper Belt.

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