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Reopening the TNOs color controversy: Centaurs bimodality and TNOs unimodality

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Abstract. We revisit the Trans–Neptunian Objects (TNOs) color controversy allegedly solved by Tegler & Romanishin (2003). We debate the statistical approach of the quoted work and discuss why it can not draw the claimed conclusions, and reanalyze their data sample with a more adequate statistical test. We find evidence for the existence of two color groups among the Centaurs. Therefore, mixing both centaurs and TNOs populations lead to the erroneous conclusion of a global bimodality, while there is no evidence for two color groups in the TNOs population alone. We use quasi–simultaneous visible color measurements published for 20 centaurs (corresponding to about half of the identified objects of this class), and conclude on the existence of two groups. With the surface evolution model of Delsanti et al. (2003) we discuss how the existence of two groups of Centaurs may be compatible with a continuous TNOs color distribution.

Key words. Kuiper Belt – methods: statistical

1. Introduction

A large population of small icy bodies exists beyond the orbit of Neptune. First speculated by Leonard (1930), Edgeworth (1943, 1949) and Kuiper (1951), their existence was observationally demonstrated by Jewitt & Luu (1993) only eleven years ago. Considered as remnants from the formation of the solar system, these Trans–Neptunian Objects (TNOs) constitute the Edgeworth–Kuiper Belt (EKB), therefore also frequently known as Kuiper Belt Objects (KBOs). Currently, more than 700 of them have been detected. A different class of objects, the Centaurs, was found by Kowal & Gehrels (1977); to date, more than 40 of these objects are known. Orbiting mainly between Jupiter and Neptune, a strict dynamical definition does not exist and frequently some objects are both classified as Centaurs and Scattered Disk Objects (SDOs). Centaurs are believed to be ex–TNOs in a transition phase between the EKB and the Jupiter–family comets (Fernandez 1980; Duncan et al. 1988). Their exact origin location in the EKB has not yet been identified. While it is currently believed Centaurs originate from the Scattered Disk Objects (Duncan & Levison 1997) – a "fuzzy" subclass of TNOs with highly eccentric and inclined orbits – an origin in the Plutinos (TNOs in a 3:2 mean motion orbital resonance with Neptune) has also been hypothesized (Yu & Tremaine 1999).

Since the very beginning of the first photometric measurements of these objects their visible color distribution always been very controversial. Tegler & Romanishin (1998, 2000) – hereafter TR98 and TR00, respectively – reported the identification of two separated color groups (blue–gray, i.e., solar like, and very red) from samples of 16 and 37 objects respectively. Other groups stated a continuous color spreading such as the precursor works by Luu & Jewitt (1996), Green et al. (1997), Barucci et al. (1999), and subsequent studies (see the review by Doressoundiram 2003, for a summary). Jewitt & Luu (2001) analyzed the statistical significance of this bimodality on TR98 and TR00 data samples and also on their own dataset of 28 objects. They concluded that both results were formally consistent with derivation from a uniform color distribution, i.e. unimodality. Finally, Tegler & Romanishin (2003) – hereafter TR03 – claimed the resolution of the TNOs color controversy, now with an enlarged sample of 55 objects (50 objects with measured $B-V$ and $V-R$ colors, and 5 with $V-R$ only). Furthermore, with Monte Carlo simulations they showed that

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with typical error bars of 0.05 mag other teams would not see any clear "gap" between their two detected groups, concluding that observational methodologies leading to smaller error bars are the basis for these color groups findings.

Whereas it is physically difficult to understand the existence of two groups of colors, several explanations have been proposed to describe the continuous color range of TNOs. First, TNOs might have real intrinsic differences. Gomes (2003) proposed a migration model explaining the present composition of the EKB as the mixing of bodies formed in very different parts of the Solar System. Assuming that the colors of bodies varied with heliocentric distance of their primordial location could explain the present color distribution (Morbidelli et al. 2003). Luu & Jewitt (1996) explored a surface evolution mechanism: a competition between reddening space weathering and bluishing collisional resurfacing, which causes the continuous color spreading. However this model predicts a surface color variation with the objects rotation (e.g. within a few hours) that has never been observed to date (Jewitt & Luu 2001); it also implies color–orbital parameters correlations very different from observations (Thébault & Doressoundiram 2003). Nevertheless, modeling is still in progress: Gil–Hutton (2002), with a more detailed space weathering process, proposed a new version of this mechanism but of difficult testing. Delsanti et al. (2003) revisited the model by Luu & Jewitt (1996) testing an additional resurfacing process: cometary activity, which is compatible with a surface homogeneity.

2. Two color groups' analysis

In the first work on TNOs bimodality (TR98), the two color groups seemed very clear. However, statistics were performed on too few objects to be really significant. Later, with an enlarged data sample, the separation between the two presumed color groups was much more tiny, even though still apparent (TR00). We should nonetheless notice that in Tegler and Romanishin's analysis Centaurs were mixed with TNOs. The irradiative and collisional environment of Centaurs should be very different of that of TNOs, hence conclusions based on the colors of both populations altogether should be taken with great care. There are few statistical tests for the detection of more than one mode (group) in a distribution. Tests based on bins, as used by TR03, should be regarded with prudence as they are too dependent on the bin's choice. We will use only the Dip Test (Hartigan & Hartigan 1985; Hartigan 1985), a distribution–free test that computes the maximum difference ("dip") between the empirical distribution function and the unimodal distribution function that minimizes the differences.

If we first restrict ourselves to the 32 objects with known $B-R$ colors and $q < 40$ AU of TR03 – a sample for which they found two groups –, the dip test confirms a bimodality for $B-R$ colors with a significance level (*SL*) of 99.7%. However, if we remove the Centaurs from this sample we have bimodality only at $SL \sim 55\%$ for the 22 objects left, while for the 10 Centaurs alone we see it at $SL = 94.7\%$. Even if the obtained *SL* is too low and the number of objects is too small to make strong conclusions, these results suggest that the bimodality found is most probably dictated by the Centaurs

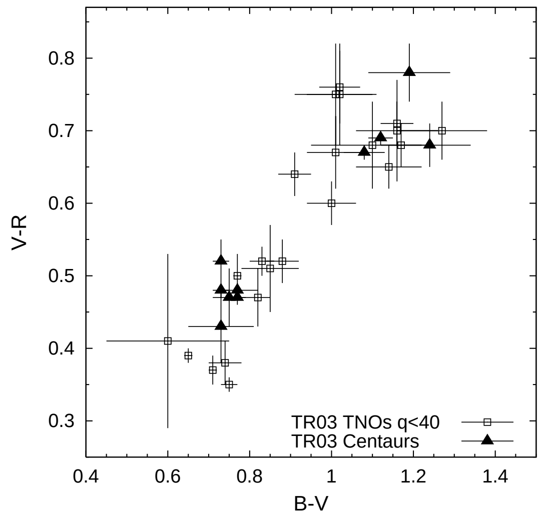

Fig. 1. $B-V$ vs. $V-R$ plot of TR03's data used to conclude for bimodality. Centaurs are highlighted and their bimodal behavior is obvious, contrarily to TNOs taken alone.

colors and can not be stated as general for TNOs (see Fig. 1). It should be noted also that, on TR03, these two groups were found without the inclusion of the "red cluster" of TNOs with perihelia distances above 40 AU. These "red cluster" objects with $q > 40$ AU are also characterized by a low inclination orbit and they most probably constitute a separate group (Levison & Stern 2001; Brown 2001) However, they appear as a red cluster while compared to the full color distribution of all other TNOs, that continuously range from neutral to red. If TNOs with $q < 40$ AU divide in two groups one neutral and another red, we can no longer consider the "red cluster" as a separate group (based on color differences) since it is apparently equal to the red one found for $q < 40$ AU. Consequently, TR03 are implicitly dealing, in their work, with not two but three groups of objects: neutral and red TNOs with $q < 40$ AU, and red TNOs with $q > 40$ AU. When all objects are included in the analysis, the bimodality disappears ($SL \sim 36\%$). If Centaurs are removed the significance level goes down to ~9% (see Figs. 2 and 3). Thus, while it does not seem justifiable to ignore the "red cluster" in the statistics, including those does "destroy" the evidence for bimodality, even with the inclusion of Centaurs. We will therefore investigate the possibility that the conclusion for two color groups is in fact being misguided by the superposition of a bimodal Centaur distribution over a continuous spread of colors of TNOs with $q < 40$ AU and a separate group of exclusively red TNOs with $q > 40$ AU or, globally, an unimodality for TNOs colors with an excess of red objects.

We therefore took all Centaurs with available quasi–simultaneous observations of $B-V$, $V-R$ and $B-R$ colors, building a data sample of 20 objects which represents almost 50% of all known Centaurs. Eight objects were obtained under the "ESO Large Program on Centaurs and TNOs", six from Peixinho et al. (2003) and two from Boehnhardt et al. (2002) and another six drawn from the "Meudon Multicolor Survey" (Doressoundiram et al. 2002). Six more were added

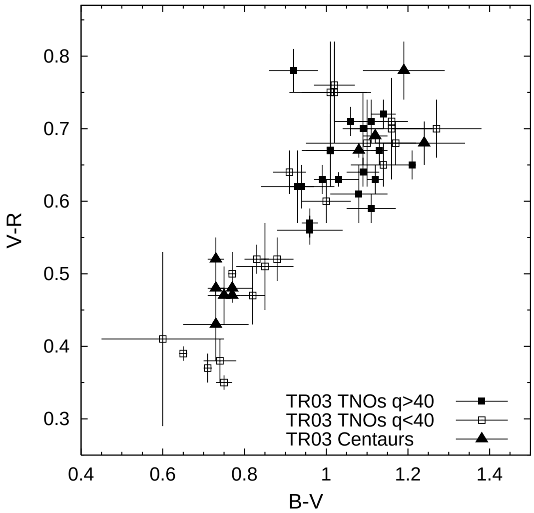

Fig. 2. $B-V$ vs. $V-R$ plot of TR03's full data. The "red cluster" of TNOs with $q > 40$ AU is included.

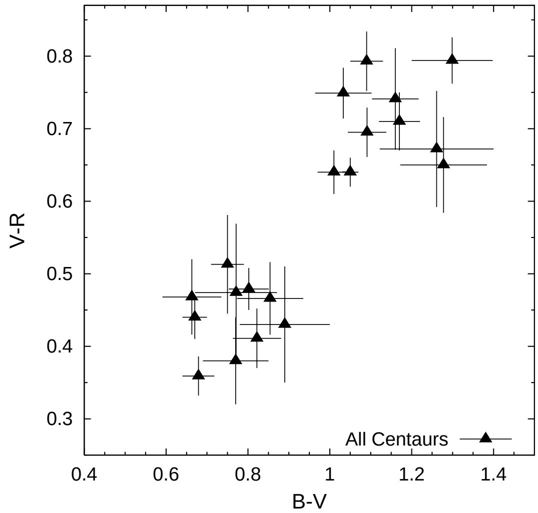

Fig. 4. $B-V$ vs. $V-R$ plot of our analyzed Centaurs' sample. The bimodality seems clear and the statistics come out highly significant.

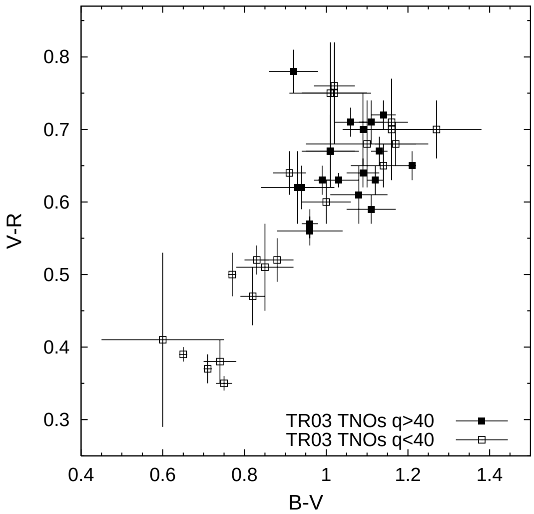

Fig. 3. $B-V$ vs. $V-R$ plot of all TNOs from TR03 excluding the Centaurs. Without the Centaurs, the absence of bimodality is clear.

from the compiled MBOSS database of Hainaut & Delsanti (2002), since their average color indexes were computed from literature using only simultaneous magnitudes (see Table 1). While TR03 observational methodology also monitored the absence of significant magnitude variations, all their Centaurs were also independently measured by the previously quoted works. The dip test on our 20 objects data sample reveals bimodality for $B-R$ colors with SL =99.5%. Furthermore, by testing $B-V$ and $V-R$ colors separately, we see that the bimodal behavior is dominated by the $V-R$ color index, since there is evidence for two $V-R$ color groups at SL = 97.7% while for $B-V$ alone it is inexistent. All dip test results are summarized in Table 2. We conclude that Centaurs' population is indeed composed by two separate $B-R$ color groups with strong evidence for a dominating $V-R$ bimodality.

In the color evolution model by Delsanti et al. (2003), TNOs are resurfaced by a competition of 1) reddening by irradiation; 2) bluishing by non-disruptive collisions between TNOs; 3) bluishing by cometary activity (i.e. uniform redeposition of neutral-colored dust lifted by gas outbursts). Simulations using known Centaurs orbits lead to very red objects regardless of the size. In the spaces between giant planets, reddening by irradiation is the dominant process while collisions are scarce; cometary activity outbursts (triggered by collisions) are also possible but with a very low probability. Observed blue Centaurs colors (like for 2060 Chiron) are compatible with a surface being recovered by the bound coma detected by Meech et al. (1997). It has been suggested that some short period comets and Centaurs should be the fragments of objects ejected from the EKB (Farinella & Davis 1996). Such fragmentation would expose some fresh, volatile rich interior that would be compatible with the existence of active and/or blue Centaurs. Delsanti et al. (2003) concluded that very red Centaurs are old, fully irradiated objects (with a thick, dark irradiated mantle that prevents from spontaneous – i.e. non collision-induced – cometary activity outbursts), while blue centaurs might be fresh fragments recovering from an ejection from the EKB. Unfortunately, their model does not currently predict the proportion of blue vs. red Centaurs. However, following this formalism, one can expect it is more likely to observe red Centaurs. We see with the sample used that the two groups (red/blue) are equally distributed. Assuming that the "excess" of blue objects is not an observational bias, we will have to invoke an injection of new blue Centaurs from the EKB. Yu & Tremaine (1999) suggested that evolution of Plutinos onto Neptune–crossing orbit may dominate the flux of Jupiter–family comets. Consequently, Centaurs' population may be mainly populated by ex–Plutinos. An excess of blue Plutinos within the same size range as Centaurs is reported by Peixinho et al. (2003) as also similar color–color correlations for Centaurs and Plutinos in opposition to SDOs correlations. These results give plausibility to our hypothesis. Nevertheless, different origins for the Centaurs population, or part of it, as an explanation of the two color groups can not be discarded.

Table 1. Centaurs' colors.

	Object	$B-V$	$V-R$	$B-R$
	2002 GO_9[a]	1.03 ± 0.07	0.75 ± 0.04	1.80 ± 0.07
	2002 DH_5[a]	0.66 ± 0.07	0.47 ± 0.05	1.05 ± 0.07
	1999 XX_{143}[a]	1.28 ± 0.11	0.65 ± 0.07	1.86 ± 0.07
	1994 TA[b]	1.26 ± 0.14	0.67 ± 0.08	1.93 ± 0.16
(63 252)	2001 BL_{41}[a]	0.82 ± 0.06	0.41 ± 0.04	1.18 ± 0.06
(60 558)	2000 EC_{98}[c]	0.85 ± 0.08	0.47 ± 0.05	1.32 ± 0.08
(55 576)	2002 GB_{10}[a]	1.09 ± 0.05	0.69 ± 0.03	1.77 ± 0.05
(54 598)	2000 QC_{243}[d]	0.67 ± 0.03	0.44 ± 0.03	1.11 ± 0.03
(52 975)	Cyllarus[d]	1.17 ± 0.05	0.71 ± 0.04	1.88 ± 0.05
(52 872)	Okyrhoe[d]	0.89 ± 0.11	0.43 ± 0.08	1.32 ± 0.11
(49 036)	Pelion[c]	0.77 ± 0.10	0.47 ± 0.10	1.25 ± 0.10
(44 539)	1999 OX_3[a]	1.16 ± 0.06	0.74 ± 0.07	1.89 ± 0.06
(33 128)	1998 BU_{48}[d]	1.01 ± 0.04	0.64 ± 0.03	1.65 ± 0.04
(31 824)	Elatus[d]	1.05 ± 0.02	0.64 ± 0.02	1.69 ± 0.02
(10 370)	Hylonome[d]	0.77 ± 0.08	0.38 ± 0.06	1.15 ± 0.08
(10 199)	Chariklo[b]	0.80 ± 0.05	0.48 ± 0.03	1.28 ± 0.06
(8405)	Asbolus[b]	0.75 ± 0.04	0.51 ± 0.07	1.26 ± 0.08
(7066)	Nessus[b]	1.09 ± 0.04	0.79 ± 0.04	1.88 ± 0.06
(5145)	Pholus[b]	1.30 ± 0.10	0.79 ± 0.03	2.09 ± 0.10
(2060)	Chiron[b]	0.68 ± 0.04	0.36 ± 0.03	1.04 ± 0.05

Colors are from, respectively, [a] Peixinho et al. (2003), [b] Hainaut & Delsanti (2002), [c] Boehnhardt et al. (2002), [d] Doressoundiram et al. (2002).

Table 2. Dip test results.

Data Sample	n[a]	Color	Dip[b]	SL[c]
TR03				
... Centaurs+TNOs: $q < 40$ AU	32	$B-R$	0.1073	99.7%
... Centaurs	10	$B-R$	0.1389	94.7%
... TNOs: $q < 40$ AU	22	$B-R$	0.0736	~55%
... Centaurs+all TNOs	50	$B-R$	0.0442	~36%
... all TNOs	40	$B-R$	0.0411	~9%
This work				
... Centaurs	20	$B-R$	0.1211	99.5%
... Centaurs	20	$B-V$	0.0750	~53%
... Centaurs	20	$V-R$	0.1156	97.7%

[a] Number of objects, [b] measure of minimum difference from unimodality, [c] dip's significance level.

3. Conclusions

In this work, we revisited the TNOs color controversy with a different and necessary twofold approach. First we argue that the dip test we used is a more appropriate tool to investigate the uni- or bi-modal distribution of colors. And second we suggest that the Centaur population has not to be mixed with TNO population in statistical studies since both populations are experiencing very different degrees of surface processing. We combined new and published datasets to show that the Centaur color distribution is bimodal while the TNO color distribution is definitively unimodal. As Centaurs are presumed escapees from the EKB, this new scheme is still compatible with evolution processes (Delsanti et al. 2003). Moreover, our results support a Plutino origin for the Centaurs. However, given the uncertainties on the transfer mechanisms of Centaurs from the EKB, we cannot rule out the possibility of true compositional diversity of Centaurs as an explanation of their color dichotomy.

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