

Transneptunian Object Taxonomy

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A taxonomic scheme based on multivariate statistics is proposed to distinguish groups of TNOs having the same behavior concerning their BVRIJ colors. As in the case of asteroids, the broadband spectrophotometry provides a first hint about the bulk compositional properties of the TNOs' surfaces. Principal components (PC) analysis shows that most of the TNOs' color variability can be accounted for by a single component (i.e., a linear combination of the colors): All the studied objects are distributed along a quasicontinuous trend spanning from "gray" (neutral color with respect to those of the Sun) to very "red" (showing a spectacular increase in the reflectance of the I and J bands). A finer structure is superimposed to this trend and four homogeneous "compositional" classes emerge clearly, and independently from the PC analysis, if the TNO sample is analyzed with a grouping technique (the G-mode statistics). The first class (designed as BB) contains the objects that are neutral in color with respect to the Sun, while the RR class contains the very red ones. Two intermediate classes are separated by the G mode: the BR and the IR, which are clearly distinguished by the reflectance relative increases in the R and I bands. Some characteristics of the classes are deduced that extend to all the objects of a given class the properties that are common to those members of the class for which more detailed data are available (observed activity, full spectra, albedo). The distributions of the classes with respect to the distance from the Sun and to the orbital inclination give some hints on the chemico-physical structure of the inner part of the Kuiper belt. An interpretation of the average broadband spectra of the four classes as the result of modifying processes (collisions, space weathering, degassing, etc.), allows us to read the proposed taxonomy in terms of the evolution of TNOs.

1. INTRODUCTION

Taxonomy (from the Greek verb *τασσεῖν* or *tassein* = "to classify" and *νόμος* or *nomos* = "law, science") was once only the science of classifying living organisms (alpha taxonomy), but later the word was applied in a wider sense, and may also refer to either a classification of things, or the principles underlying the classification. Almost anything — animate objects, inanimate objects, places, and events — may be classified according to some taxonomic scheme. Such an approach to studying physical properties

became an efficient tool in asteroid investigations, which enabled the expansion of our knowledge of physical properties of well-studied asteroids within a taxon to other members belonging to the same taxon.

Multivariate and canonical (parametrical and/or nonparametrical) analysis of the color distribution of transneptunian objects (TNOs) and associated families and their orbital parameters, together with recently developed cluster analysis methods, could be used in order to set the basis of taxonomy. The objectives are to demonstrate, rule out, or constrain the several dynamical, thermal, and surface evolution mod-

els and characterize the several dynamical subclasses of TNOs by their surface and orbital properties, defining or constraining their boundaries.

Wood and Kuiper (1963) suggested, on the basis of the distribution of about 40 asteroids in the U–B and B–V plot, the existence of two different compositional classes clustering around the color indices of the Moon and the Sun. These groups were the ancestors of the currently used asteroid S and C classes, respectively.

Tholen and Barucci (1989) summarized the results of their asteroid taxonomies for about 400 asteroids obtained by means of independent multivariate statistical techniques [the principal components (PC) analysis based on eight-color data from *Zellner et al.* (1985) and the G-mode analysis based on the same eight colors database to which the IRAS albedo data from *Tedesco et al.* (1992) were added]. *Tedesco et al.* (1989) obtained three-parameter taxonomy analyzing more than 350 asteroids described by two colors indices (U–V and v–x) and the visual albedo. All these methods provided a similar classification scheme separating the asteroid population into a dozen compositionally homogeneous groups, as outlined by *Barucci and Fulchignoni* (1990).

Analyzing the B–V and V–R colors of 13 TNOs and Centaurs, *Tegler and Romanishin* (1998) obtained two groups, one very red and the other quite neutral with respect to the Sun. *Barucci et al.* (2001) applied both techniques used in classifying the asteroids to a sample of 22 TNOs and Centaurs characterized by four colors (B–V, V–R, V–I, and V–J). The results indicate a clear compositional trend within the examined sample and suggest the possible existence of four homogeneous groups. The increase of the available data allowed *Fulchignoni et al.* (2003) and *Barucci et al.* (2005a) to confirm this result at a higher significance level, analyzing samples of 34 and 51 objects respectively.

An interesting attempt to characterize the TNOs on the basis of their orbital elements and some physical properties has been recently carried out by *De Sanctis et al.* (2006), who used the G mode to analyze 81 TNOs chosen among those with well-known dynamical parameters, described by the color indices B–V and V–R, the absolute magnitude H, the orbital inclination i , orbital eccentricity e , and semimajor axis a . The G-mode analysis separates the 81 objects of the sample in five groups, well separated for the dynamical parameters and less separated in colors. The obtained groups are close to the well-known dynamical ones (classical, Plutinos, scattered, and detached), but the classification firmly identifies two different types of classical objects, corresponding to the “so-called” dynamically cold and hot classical population. Moreover, they found trends and correlations within the members of the different groups.

To distinguish groups of objects with similar properties we need to have a statistically representative dataset. However, the knowledge of physical properties of TNOs is still very limited: To date, the available information concerning TNOs include (1) orbital parameters (known for all the objects with different degrees of precision) and (2) broadband

B, V, R, I photometry for about 130 objects; for approximately 70 of them J data are also available, while H and K photometry has been obtained for only about 55 of them.

Hereafter we present the first taxonomic scheme used to obtain a classification of the TNOs. In fact, when dealing with a large number of objects, it is very important to distinguish groups of objects with similar properties, preferably based on measured common characteristics.

2. DATA AND STATISTICAL METHODS

We successively analyzed two homogeneous TNO samples: (1) 67 objects described by four color indices (B–V, V–R, V–I, V–J); (2) 55 objects described by six color indices (B–V, V–R, V–I, V–J, V–H, V–K). The list of objects and their colors together with the references to the original data are given in Table 1.

When multiple observations of an object were available, for the colors we adopted their mean values weighted with the inverse of the error of individual measurement and the standard deviation was assumed as the error. In the case of a single measurement we restricted our consideration to those objects for which colors were determined with an error less than 0.1 mag for BVRIJ colors. The selected data represent a homogeneous dataset in B, V, R, I, J, H, and K bands in general obtained by the same observer during the same run, or intercalibrated through the V measurements. We used nonsimultaneous V and the JHK set of magnitudes in a few cases when it was possible to recalculate V magnitude to the epoch of JHK measurements taking into account the geometry of observations.

The analysis has been carried out using both principal component analysis (PCA) (*Reyment and Joreskog*, 1993) and G-mode analysis (*Coradini et al.*, 1977; *Fulchignoni et al.*, 2000).

The principal components (PC) are linear combinations of the original variables whose coefficients reflect the relative importance of each variable (color) within each principal component. These coefficients are the eigenvectors of the variance-covariance matrix of the colors. The sum of the eigenvalues of this matrix (which is equal to its trace) accounts for the total variance of each sample. Each eigenvalue reflects the percentage of the total variance contributed by each principal component.

We analyzed the same samples with the G-mode multivariate statistics (*Coradini et al.*, 1977), which allowed us to investigate the existence of a finer structure of the samples. G-mode statistics were applied to our samples of 67 and 55 objects described by four and six variables, respectively. The total number of degrees of freedom (268 and 330 respectively) allow us to use this type of statistics. The goal of the analysis is to find groups of objects that have a homogeneous behavior, if any, in terms of their physical characteristics (variables) under consideration. The method provides a quantitative estimation of the weight of each variable in separating the groups. We refer the reader to the quoted literature for details on both PC and G-mode statistics.

TABLE 1. Average colors of the selected sample objects.

Object/Type*	B-V	V-R	V-I	V-J	V-H	V-K	References
Sun	0.67	0.36	0.69	1.08	1.37	1.43	1,2
2060 Chiron/C	0.63 ± 0.02	0.35 ± 0.01	0.70 ± 0.04	1.13 ± 0.01	1.43 ± 0.01	1.50 ± 0.03	14,15,16,17,46
5145 Pholus/C	1.25 ± 0.03	0.77 ± 0.01	1.58 ± 0.01	2.57 ± 0.03	2.94 ± 0.04	2.93 ± 0.04	8,15,16,17,46
7066 Nessus/C	1.09 ± 0.01	0.79 ± 0.01	1.47 ± 0.03	2.29 ± 0.01	2.57 ± 0.10	2.57 ± 0.10	14,15,16,17
8405 Asbolus/C	0.75 ± 0.01	0.47 ± 0.02	0.98 ± 0.01	1.65 ± 0.02	2.06 ± 0.04	2.22 ± 0.08	15,16,17,18,19
10199 Chariklo/C	0.80 ± 0.02	0.48 ± 0.01	1.01 ± 0.01	1.73 ± 0.03	2.14 ± 0.03	2.21 ± 0.03	3,5,16,17,42
10370 Hylonome/C	0.69 ± 0.06	0.43 ± 0.02	0.96 ± 0.03	1.32 ± 0.01	1.50 ± 0.08	1.77 ± 0.09	5,9,15,16,17,42
15788 1993 SB/R	0.80 ± 0.02	0.47 ± 0.01	1.01 ± 0.01	1.43 ± 0.11	1.50 ± 0.08	1.77 ± 0.09	3,4,6,20,22,23
15789 1993 SC/R	1.08 ± 0.08	0.70 ± 0.06	1.49 ± 0.04	2.42 ± 0.07	2.82 ± 0.21	2.78 ± 0.20	3,4,7,8,14,
15820 1994 TB/R	1.10 ± 0.02	0.69 ± 0.02	1.43 ± 0.03	2.37 ± 0.09	2.78 ± 0.09	2.93 ± 0.09	3,4,8,9,11,12,20,46
15874 1996 TL ₆₆ /S	0.73 ± 0.03	0.37 ± 0.02	0.72 ± 0.01	1.46 ± 0.10	1.81 ± 0.17	1.77 ± 0.15	3,4,5,7,10,46
15875 1996 TP ₆₆ /R	1.05 ± 0.06	0.66 ± 0.02	1.31 ± 0.07	2.26 ± 0.08	2.42 ± 0.08	2.44 ± 0.08	3,4,5,7,9,10,46
19299 1996 SZ ₄ /R	0.75 ± 0.08	0.52 ± 0.03	0.97 ± 0.14	1.87 ± 0.13	0.79 ± 0.20	1.60 ± 0.18	3,4,22,24
19308 1996 TO ₆₀ /Cl	0.67 ± 0.03	0.40 ± 0.02	0.75 ± 0.02	1.00 ± 0.10	2.29 ± 0.03	2.32 ± 0.04	3,5,7,10,25,26,27
19521 Chaos/Cl	0.94 ± 0.03	0.62 ± 0.01	1.19 ± 0.05	1.89 ± 0.03	2.55 ± 0.07	2.52 ± 0.08	4,9,10,11,12,22,46
20000 Varuna/Cl	0.88 ± 0.02	0.61 ± 0.02	1.24 ± 0.02	1.99 ± 0.01	0.59 ± 0.06	0.49 ± 0.05	4,6,9,10,11,12,28,46
24835 1995 SM ₅₅ /Cl	0.65 ± 0.01	0.38 ± 0.02	0.71 ± 0.02	1.07 ± 0.05	0.79 ± 0.20	1.60 ± 0.18	3,4,6,20,24
24952 1997 QJ ₄ /R	0.76 ± 0.04	0.43 ± 0.06	0.81 ± 0.05	1.23 ± 0.31	2.88 ± 0.04	3.03 ± 0.08	11,13,24,29,46
26181 1996 GQ ₃₁ /R	1.01 ± 0.01	0.71 ± 0.01	1.42 ± 0.01	2.39 ± 0.04	2.91 ± 0.02	2.96 ± 0.07	4,11,12,22,46
26308 1998 SM ₁₆₅ /R	0.98 ± 0.02	0.65 ± 0.04	1.30 ± 0.01	2.36 ± 0.01	2.17 ± 0.05	2.19 ± 0.05	3,9,11,20,29,30,46
26375 1999 DE ₉ /S	0.97 ± 0.03	0.58 ± 0.01	1.15 ± 0.01	1.84 ± 0.04	2.18 ± 0.11	1.97 ± 0.09	46
28978 Ixion/R	1.03 ± 0.03	0.61 ± 0.03	1.19 ± 0.04	1.88 ± 0.09	2.18 ± 0.11	1.97 ± 0.09	46
29981 1999 TD ₁₀ /S	0.75 ± 0.02	0.49 ± 0.02	1.02 ± 0.03	1.88 ± 0.07	2.31 ± 0.10	2.43 ± 0.10	4,20,28,46
31824 Eliatus/C	1.03 ± 0.03	0.66 ± 0.01	1.28 ± 0.01	2.09 ± 0.07	2.48 ± 0.09	2.51 ± 0.09	9,12,17,28, 46
32532 Thereus/C	0.75 ± 0.01	0.49 ± 0.02	0.94 ± 0.01	1.69 ± 0.05	2.14 ± 0.07	2.30 ± 0.05	17,31,32,46
32929 1995 QY ₉ /R	0.70 ± 0.02	0.51 ± 0.04	0.86 ± 0.06	2.02 ± 0.01	2.79 ± 0.11	2.60 ± 0.11	4,6,9,14
33128 1998 BU ₄₈ /S	0.95 ± 0.08	0.64 ± 0.02	1.18 ± 0.01	2.27 ± 0.05	2.21 ± 0.01	2.23 ± 0.01	9,11,12,13,17
33340 1998 VG ₄₄ /R	0.90 ± 0.01	0.59 ± 0.01	1.18 ± 0.08	1.81 ± 0.01	2.27 ± 0.05	2.23 ± 0.01	4,9,10,46
35671 1998 SN ₁₆₅ /Cl	0.71 ± 0.06	0.42 ± 0.03	0.82 ± 0.01	1.27 ± 0.05	2.27 ± 0.05	2.37 ± 0.06	3,4,6,9,20
38628 Huyar/R	0.96 ± 0.02	0.57 ± 0.02	1.20 ± 0.02	1.95 ± 0.02	2.27 ± 0.05	2.37 ± 0.06	3,4,9,24,28,33,34,46
40314 1999 KR ₁₆ /D	1.06 ± 0.03	0.76 ± 0.01	1.50 ± 0.03	2.37 ± 0.10	2.95 ± 0.12	2.97 ± 0.12	3,11,13,36
42301 2001 UR ₁₆₃ /R	1.30 ± 0.11	0.84 ± 0.01	1.46 ± 0.11	2.37 ± 0.06	2.86 ± 0.08	2.34 ± 0.09	43,46
42355 2002 CR ₄₆ /S	0.83 ± 0.07	0.55 ± 0.05	0.99 ± 0.06	1.83 ± 0.09	2.18 ± 0.12	2.34 ± 0.09	46
44594 1999 OX ₃ /S	1.15 ± 0.02	0.69 ± 0.02	1.39 ± 0.02	2.20 ± 0.05	2.63 ± 0.05	2.63 ± 0.10	4,9,17,22,35,43,46
47171 1999 TC ₃₆ /R	1.03 ± 0.02	0.69 ± 0.01	1.33 ± 0.02	2.32 ± 0.01	2.70 ± 0.03	2.70 ± 0.02	4,9,10,11,12,30,41,46
47932 2000 GN ₁₇₁ /R	0.92 ± 0.01	0.62 ± 0.01	1.22 ± 0.02	1.84 ± 0.08	2.21 ± 0.14	2.38 ± 0.14	4,13,24,46
48639 1995 TL ₈ /Cl	1.04 ± 0.01	0.69 ± 0.01	1.33 ± 0.01	2.42 ± 0.05	2.82 ± 0.09	2.80 ± 0.09	11,20
52872 Okyrhoe/JFC	0.75 ± 0.04	0.47 ± 0.02	0.97 ± 0.02	1.93 ± 0.10	2.40 ± 0.12	2.52 ± 0.10	9,17,20,28,41,46
52975 Cyllarus/C	1.13 ± 0.04	0.69 ± 0.01	1.36 ± 0.03	2.42 ± 0.07	2.87 ± 0.11	2.77 ± 0.11	9,10,11,12,17
54598 Bienor/S	0.69 ± 0.02	0.47 ± 0.02	0.92 ± 0.05	1.74 ± 0.03	2.14 ± 0.05	2.27 ± 0.11	9,11,12,17,30,41,46
55565 2002 AW ₁₉₇ /Cl	0.90 ± 0.03	0.62 ± 0.03	1.18 ± 0.03	1.82 ± 0.06	2.15 ± 0.08	2.38 ± 0.10	39

TABLE 1. (continued).

Object/Type*	B-V	V-R	V-I	V-J	V-H	V-K	References
55576 Amycus/C	1.11 ± 0.01	0.71 ± 0.01	1.38 ± 0.05	2.14 ± 0.03	2.44 ± 0.03	2.37 ± 0.03	39,46
55637 2002 UX ₂₅ /CI	0.94 ± 0.06	0.54 ± 0.06	1.13 ± 0.05	1.82 ± 0.09	2.22 ± 0.10	2.22 ± 0.11	46
58534 Logos/CI	0.99 ± 0.01	0.73 ± 0.06	1.29 ± 0.03	1.84 ± 0.37			3,6,9,10,25
60558 Echeclus/JFC	0.85 ± 0.08	0.47 ± 0.01	0.94 ± 0.02	1.49 ± 0.10	2.05 ± 0.12	2.39 ± 0.11	12,17,24
63252 2001 BL ₄₁ /C	0.72 ± 0.05	0.48 ± 0.03	1.06 ± 0.03	1.65 ± 0.07	2.02 ± 0.09	2.26 ± 0.09	17,29,30,35
66652 1999 RZ ₂₅₃ /CI	0.82 ± 0.17	0.65 ± 0.06	1.30 ± 0.06	2.01 ± 0.07	2.49 ± 0.11	2.59 ± 0.09	4,11,20,37
79360 1997 CS ₂₉ /CI	1.08 ± 0.03	0.66 ± 0.04	1.25 ± 0.03	2.06 ± 0.03	2.44 ± 0.08	2.48 ± 0.09	3,4,5,9,10,11
82075 2000 YW ₁₃₄ /R	0.87 ± 0.03	0.39 ± 0.02	1.07 ± 0.03	1.68 ± 0.12	2.02 ± 0.16	2.18 ± 0.16	46
82155 2001 FZ ₁₇₃ /S	0.87 ± 0.06	0.58 ± 0.04	1.07 ± 0.05	1.92 ± 0.12	2.09 ± 0.17	2.39 ± 0.16	46
83982 Crantor/C	1.10 ± 0.04	0.76 ± 0.01	1.44 ± 0.01	2.46 ± 0.02	2.83 ± 0.02	2.79 ± 0.02	39,46
87555 2000 QB ₂₄₃ /S	0.77 ± 0.05	0.38 ± 0.05	1.36 ± 0.08	1.48 ± 0.07	2.09 ± 0.11		46
90377 Sedna/D	1.23 ± 0.09	0.76 ± 0.09	1.37 ± 0.09	2.32 ± 0.06	2.61 ± 0.06	2.66 ± 0.07	21
90482 Orcus/R	0.68 ± 0.04	0.37 ± 0.04	0.74 ± 0.04	1.08 ± 0.04	1.21 ± 0.04	1.25 ± 0.04	40
91133 1998 HK ₁₅₁ /R	0.72 ± 0.05	0.49 ± 0.03	0.88 ± 0.01	1.57 ± 0.09			4,9,10
95626 2002 GZ ₃₂ /C	0.73 ± 0.06	0.51 ± 0.04	0.92 ± 0.05	1.63 ± 0.08	2.08 ± 0.10	2.19 ± 0.10	46
118228 1996 TQ ₆₆ /R	1.19 ± 0.02	0.66 ± 0.03	1.44 ± 0.14	2.41 ± 0.08			3,4,5,6
134860 2000 OJ ₆₇ /CI	1.05 ± 0.06	0.67 ± 0.05	1.27 ± 0.07	1.98 ± 0.10	2.26 ± 0.14	2.33 ± 0.16	9,11
136108 2003 EL ₆₁ /CI	0.63 ± 0.03	0.34 ± 0.02	0.68 ± 0.02	1.05 ± 0.02	1.01 ± 0.04	0.94 ± 0.05	45
136199 Eris/D	0.71 ± 0.02	0.45 ± 0.02	0.78 ± 0.02	1.01 ± 0.02	0.72 ± 0.04	0.32 ± 0.05	44
1996 TS ₆₆ /CI	1.06 ± 0.03	0.73 ± 0.03	1.31 ± 0.08	1.87 ± 0.03	2.52 ± 0.08		3,4,5,7
1998 WU ₂₄ /?	0.78 ± 0.03	0.53 ± 0.04	0.99 ± 0.03	1.67 ± 0.04			38
1999 CD ₁₅₈ /R	0.86 ± 0.01	0.52 ± 0.02	1.10 ± 0.04	1.86 ± 0.07	2.30 ± 0.07	2.33 ± 0.08	11,12
2000 OK ₆₇ /CI	0.82 ± 0.06	0.60 ± 0.05	1.22 ± 0.08	2.42 ± 0.08	2.88 ± 0.11	2.92 ± 0.12	9,11,12
2000 PE ₃₀ /D	0.75 ± 0.04	0.33 ± 0.06	0.75 ± 0.08	1.65 ± 0.08	2.09 ± 0.08	2.32 ± 0.11	9,11,12,46
2001 CZ ₃₁ /CI	0.60 ± 0.15	0.50 ± 0.10	0.80 ± 0.15	1.53 ± 0.10	2.08 ± 0.14	2.24 ± 0.14	11,13
2001 QF ₂₉₈ /R	0.65 ± 0.02	0.36 ± 0.02	0.76 ± 0.06	1.30 ± 0.10	1.53 ± 0.14	1.69 ± 0.15	11,43,46
2003 AZ ₈₄ /R	0.61 ± 0.08	0.45 ± 0.07	0.80 ± 0.07	1.46 ± 0.10	1.48 ± 0.14	1.39 ± 0.16	46

*Type (from the chapter by Gladman et al.): C = Centaurs, CI = classical, R = resonant, S = scattered, D = detached, JFC = Jupiter-family comet orbit, ? = unusual, Halley-family comet.
References: [1] *Hardlop* (1980); [2] *Hartmann et al.* (1982); [3] *Jewitt and Luu* (2001); [4] *McBride et al.* (2003); [5] *Tegler and Romanishin* (1998); [6] *Gil-Hutton and Licandro* (2001); [7] *Jewitt and Luu* (1998); [8] *Tegler and Romanishin* (1997); [9] *Doressoundiram et al.* (2002); [10] *Boehnhardt et al.* (2001); [11] *Delsanti et al.* (2006); [12] *Delsanti et al.* (2004); [13] *Sheppard and Jewitt* (2002); [14] *Luu and Jewitt* (1996); [15] *Davies et al.* (1998); [16] *Davies et al.* (2000); [17] *Bauer et al.* (2003); [18] *Romanishin et al.* (1997); [19] *Roman-Martin et al.* (2002); [20] *Delsanti et al.* (2001); [21] *Barucci et al.* (1999); [22] *Tegler and Romanishin* (2000); [23] *Davies et al.* (1997); [24] *Boehnhardt et al.* (2002); [25] *Davies* (2000); [26] *Hainaut et al.* (2000); [27] *Barucci et al.* (1999); [28] *Tegler and Romanishin* (2003); [29] *Doressoundiram et al.* (2003); [30] *Tegler et al.* (2003); [31] *Barucci et al.* (2002); [32] *Farnham and Davies* (2003); [33] *Ferrin et al.* (2001); [34] *Schaefer and Rabinowitz* (2002); [35] *Peixinho et al.* (2004); [36] *Trujillo and Brown* (2002); [37] *Doressoundiram et al.* (2001); [38] *Davies et al.* (2001); [39] *Doressoundiram et al.* (2005a); [40] *De Bergh et al.* (2005); [41] *Dotto et al.* (2003); [42] *McBride et al.* (1999); [43] *Doressoundiram et al.* (2005b); [44] *Brown et al.* (2005); [45] *Trujillo et al.* (2007); [46] *Doressoundiram et al.* (2007).

TABLE 2. Eigenvectors, eigenvalues, and percentage of total variance contributed by each eigenvalue from the PC analysis of the samples of 67 and 55 TNOs.

Sample of 67 TNOs						
Variable	1	2	3	4		
B–V	0.311	0.508	0.674	–0.436		
V–R	0.235	0.241	0.290	0.896		
V–I	0.450	0.579	–0.678	–0.054		
V–J	0.804	–0.591	0.034	–0.063		
Eigenvalues	0.269	0.015	0.004	0.002		
Percentage of total variance	92.892	5.220	1.269	0.619		
Sample of 55 TNOs						
Variable	1	2	3	4	5	6
B–V	0.147	0.427	0.332	–0.406	0.721	0.035
V–R	0.116	0.280	0.167	–0.006	–0.314	0.884
V–I	0.234	0.477	0.405	–0.134	–0.569	–0.461
V–J	0.440	0.413	–0.287	0.713	0.202	–0.057
V–H	0.605	–0.076	–0.578	–0.530	–0.111	–0.011
V–K	0.592	–0.579	0.530	0.166	0.070	0.032
Eigenvalues	0.880	0.044	0.011	0.004	0.003	0.001
Percentage of total variance	93.312	4.664	1.199	0.409	0.304	0.112

3. RESULTS

We applied PCA successively to the dataset of 67 TNOs described by 4 variables (B–V, V–R, V–I, and V–J color indices) and to the subset of 55 TNOs described by 6 variables (B–V, V–R, V–I, V–J, V–H, and V–K color indices). The eigenvectors, percentages of total variance contributed by each eigenvector, and eigenvalues of the variance-covariance matrix of the two analyzed samples are reported in Table 2.

These data show that in both cases (the results of the PC analysis carried out on 67 and 55 samples respectively) the first principal component (PC1) accounts for most of the variance of the sample (93%); the second principal component (PC2) adds only 4–5% to the total variance.

The first and the second principal components account for about 98% of the total variance, therefore the PC1 vs. PC2 plane contains practically all the information on the variance of the variables characterizing the considered sample. This analysis establishes the existence of a quasicontinuous trend from neutral to very red objects along the PC1 axis. It is also possible to infer from these results that the degree of reddening is the main distinctive character of the TNO population. The predominance of PC1 (i.e., of V–I and V–J colors in the first case and V–H and V–K colors in the second one) in characterizing TNO behavior is shown by the PC1 scores, which span three times more than PC2. The objects having a neutral color with respect to the Sun have the lower values of the PC1 scores and fall in the left part of the histogram shown in Fig. 1; for larger PC1 scores the

objects are redder and redder. The object number density along the PC1 is not homogeneous, indicating the presence of some grouping that overlaps the continuous trend. In Fig. 1 the histogram represents the number of the objects projected onto the PC1, clearly showing four peaks. These groups of objects constitute a finer structure overlapping the general trend from neutral to very red spectra resulting from the PC analysis.

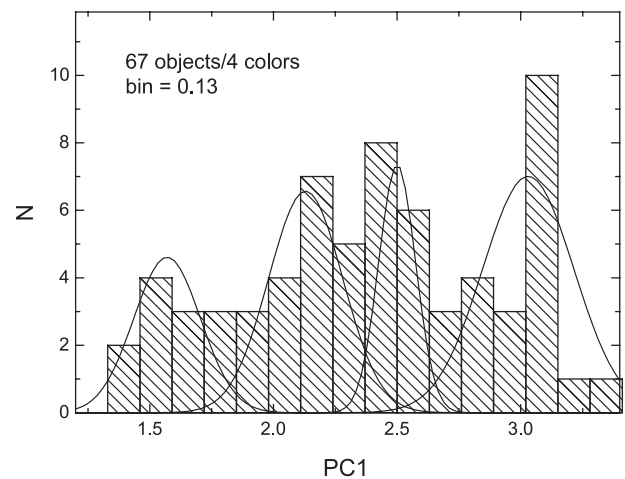


Fig. 1. Histogram showing the distribution of TNOs vs. the PC1 scores. The four superimposed curves represent the four classes obtained by the G mode. The Gaussians described by the parameters characterizing each class (average, standard deviation, and number of objects as reported in Table 3) are projected on the PC1 axis.

The relationship between the variables used is probably nonlinear, so the PC analysis does not allow us to discriminate among the intrinsic structure of these groups. To recognize the structure of the number density distribution on the PC1 axis we used the G-mode method.

When a sample of 67 objects was considered and four colors (B–V, V–R, V–I, and V–J) were taken as variables, for a total of $67 \times 4 = 268$ degrees of freedom, four groups were recognized at a >99% confidence level. The weight of each variable in separating these groups is 31% for B–V color, 26% for V–I, 22% for V–R, and 21% for V–J, indicating that the B–V variable weight was one-third more than the others in discriminating the classes. One object (2000 QB₂₄₃) was not attributed to any class, forming a “single object group” as in the Tholen asteroid taxonomy: 4 Vesta, 1862 Apollo, and 349 Dembowska formed the V, Q, and R classes (Tholen and Barucci, 1989). Today, many small asteroids populate the V class, and some new objects have been added to the R and Q classes (Binzel and Xu, 1993; Bus and Binzel, 2002).

4. TAXONOMY BASED ON COLOR INDICES

A two-letter designation for the identified groups is introduced to distinguish TNO taxonomy from asteroid taxonomy. Objects having neutral colors with respect to the Sun are classified as the BB (“blue”) group; those having a very high red color are classified as RR (“red”). The BR group consists of objects with an intermediate blue-red color, while the IR group includes moderately red objects. For a detailed discussion about the spectral characteristics/composition of objects belonging to the different classes, see the chapter by Barucci et al.

The BB group contains objects having neutral reflectance spectra. Typical objects of the group are 2060 Chiron, 19308 (1996 TO₆₆), 15874 (1996 TL₆₆), 90482 Orcus, 136108 (2003 EL₆₁), and 136199 Eris. The typical spectra are flat, somewhat bluish in the near-infrared. The ice absorption bands seem generally stronger than in the other groups, although the H₂O ice presence in the Chiron spectrum seems connected to temporal/orbital variations, and the spectrum of 1996 TL₆₆ is the only one, at present, that is completely flat. A group of these BB objects, which have been found to belong to the same dynamical family as 136108 (2003 EL₆₁), show deeper H₂O ice absorption bands (see the chapter by Brown), which has been interpreted as a consequence of the collisional fragmentation of the family parent body.

The BR group is an intermediate group between BB and IR, even though its color is closer to the behavior of the IR group. Typical members of this taxon are 8405 Asbolus, 10199 Chariklo, 54598 Bienor, and 32532 Thereous. A small percentage of H₂O ice is present on the surface of these objects.

The IR group is less red than the RR group. Typical members of this taxon are 19521 Chaos, 20000 Varuna,

38628 Huya, 47932 (2000 GN₁₇₁), 26375 (1999 DE₉), and 555565 (2002 AW₁₉₇). Three of these objects seem to contain hydrous silicates on the surface.

The RR group contains the reddest objects in the solar system, showing a small percentage of ice on the surface. Some well-observed objects are members of this group, such as 47171 (1999 TC₃₆), 55576 (2002 GB₁₀), 83982 (2002 GO₉), and 90377 Sedna. 5145 Pholus, 26181 (1996 GQ₂₁), and 55638 (2002 VE₉₅) contain methanol on their surfaces, and this could imply a primitive chemical nature (see chapter by Barucci et al.).

Unfortunately, we cannot associate an albedo range with each taxonomic group because of the lack of albedo data. The albedo of TNOs is a fundamental property that is still largely undersampled; some albedo measurements have been obtained by the Spitzer Space Telescope (see the chapter by Stansberry et al.), and in the future, ALMA will provide direct measurements of the sizes of TNOs and consequently their albedos. Further developments are also expected from ESA Herschel Space Observatory, which will cover the far-infrared to submillimeter portions of the spectrum (from 60 to 670 μm).

The G-mode method has been applied to analyze a set of 55 objects for which the B–V, V–R, V–I, V–J, V–H, and V–K colors were taken as variables ($55 \times 6 = 330$ d.o.f.). The four groups are also well separated at a confidence level of 99%. The weight of each variable in separating these groups is 21% for the V–I color, 17% for V–J, 16% for V–R, V–K, and V–H, and 14% for B–V, showing that all the variables play the same role in discriminating the taxons. The number of samples, the color average value, and the relative standard deviation for each group obtained by G-mode analysis for both analyzed samples are given in Table 3.

Note that the G mode applied to the sample described by six variables gives always four groups, where the average and the standard deviation values for the first four colors are the same obtained by running the analysis with only four variables. Moreover, these average colors for the taxonomic groups practically coincide with the values obtained from the G-mode analysis of 51 objects (Barucci et al., 2005a). Thus, increasing the number of objects and expanding the set of variables does not result in any significant variations in the identified taxons, clearly indicating the stability of the proposed taxonomy.

The G mode has been extended (Fulchignoni et al., 2000) to assign to one of the previously defined taxons any object for which the same set of variables become available. Moreover, even if a subset of the variables used in the initial development of the taxonomy is known for an object, the algorithm allows us to give at least a preliminary indication of its relevance to a given group. The lack of information on a variable is reflected by the fact that an object could be assigned to two different taxons when the missing variable is the one that discriminates between these taxons.

We applied this algorithm to each of the 66 other TNOs for which B–V, V–R, and V–I colors are available. More-

TABLE 3. The relative number of samples, average colors, and relative standard deviation for the taxons obtained by the G mode.

Sample of 67 TNOs and Centaurs							
Class	N	B–V	V–R	V–I	V–J		
BB	13	0.68 ± 0.05	0.39 ± 0.04	0.75 ± 0.05	1.23 ± 0.21		
BR	18	0.75 ± 0.05	0.49 ± 0.04	0.96 ± 0.05	1.69 ± 0.19		
IR	11	0.92 ± 0.05	0.59 ± 0.04	1.17 ± 0.05	1.87 ± 0.06		
RR	24	1.07 ± 0.07	0.70 ± 0.04	1.36 ± 0.09	2.25 ± 0.19		
Sample of 55 TNOs and Centaurs							
Class	N	B–V	V–R	V–I	V–J	V–H	V–K
BB	10	0.67 ± 0.05	0.38 ± 0.04	0.74 ± 0.04	1.22 ± 0.23	1.27 ± 0.49	1.33 ± 0.60
BR	12	0.75 ± 0.07	0.47 ± 0.03	0.97 ± 0.08	1.69 ± 0.13	2.13 ± 0.12	2.29 ± 0.11
IR	10	0.91 ± 0.04	0.58 ± 0.04	1.14 ± 0.07	1.86 ± 0.06	2.21 ± 0.09	2.31 ± 0.09
RR	23	1.05 ± 0.11	0.69 ± 0.05	1.35 ± 0.10	2.26 ± 0.18	2.66 ± 0.22	2.66 ± 0.25

TABLE 4. Proposed classification on the base of the G-mode classification results; for each TNO and Centaur the respective taxon and the number of colors (N) used in classifying it are reported.

Object	Class	N	Object	Class	N
2060 Chiron	BB	6	40314 1999 KR ₁₆	RR	6
5145 Pholus	RR	6	42301 2001 UR ₁₆₃	RR	5
7066 Nessus	RR	6	42355 2002 CR ₄₆	BR	6
8405 Asbolus	BR	6	44594 1999 OX ₃	RR	6
10199 Chariklo	BR	6	47171 1999 TC ₃₆	RR	6
10370 Hylonome	BR	6	47932 2000 GN ₁₇₁	IR	6
15788 1993 SB	BR	4	48639 1995 TL ₈	RR	6
15760 1992 QB ₁	RR	3	49036 Pelion	BR	3
15788 1993 SB	BR	3	52975 Cyllarus	RR	6
15789 1993 SC	RR	6	54598 Bienor	BR	6
15820 1994 TB	RR	6	52872 Okyrhoe	BR	6
15874 1996 TL ₆₆	BB	6	55565 2002 AW ₁₉₇	IR	6
15875 1996 TP ₆₆	RR	6	55576 Amycus	RR	6
15883 1997 CR ₂₉	BR	3	55636 2002 TX ₃₀₀	BB	3
16684 1994 JQ ₁	RR	3	55637 2002 UX ₂₅	IR	6
19255 1994 VK ₈	RR	3	55638 2002 VE ₉₅	RR	6
19299 1996 SZ ₄	BR	4	58534 Logos	RR	4
19308 1996 TO ₆₆	BB	6	59358 1999 CL ₁₅₈	BR	3
19521 Chaos	IR	6	60454 2000 CH ₁₀₅	RR	3
20000 Varuna	IR	6	60558 Echeclus	BR	6
24835 1995 SM ₅₅	BB	6	60608 2000 EE ₁₇₃	BR	3
24952 1997 QJ ₄	BR-BB	3	60620 2000 FD ₈	RR	3
26181 1996 GQ ₂₁	RR	6	60621 2000 FE ₈	BR	3
26308 1998 SM ₁₆₅	RR	6	63252 2001 BL ₄₁	BR	6
26375 1999 DE ₉	IR	6	66452 1999 OF ₄	RR	3
28978 Ixion	IR	6	66652 1999 RZ ₂₅₃	RR	6
29981 1999 TD ₁₀	BR	6	69986 1998 WW ₂₄	BR	3
33001 1997 CU ₂₉	RR	3	69988 1998 WA ₃₁	BR	3
31824 Elatus	RR	6	69990 1998 WU ₃₁	RR	3
32532 Thereus	BR	6	79360 1997 CS ₂₉	RR	6
32929 1995 QY ₉	BR	4	79978 1999 CC ₁₅₈	IR	3
33128 1998 BU ₄₈	RR	6	79983 1999 DF ₉	RR	3
33340 1998 VG ₄₄	IR	6	82075 2000 YW ₁₃₄	BR	6
35671 1998 SN ₁₆₅	BB	4	82155 2001 FZ ₁₇₃	IR	6
38083 Rhadamanthus	BR	3	82158 2001 FP ₁₈₅	IR	3
38084 1999 HB ₁₂	BR	3	83982 Crantor	RR	6
38628 Huya	IR	6	85633 1998 KR ₆₅	RR	3

TABLE 4. (continued).

Object	Class	N	Object	Class	N
86177 1999 RY ₂₁₅	BR	3	1998 WV ₃₁	BR	3
87555 2000 QB ₂₄₃	U	5	1998 WZ ₃₁	BB	3
90377 Sedna	RR	6	1998 XY ₉₅	RR	3
90482 Orcus	BB	6	1999 CD ₁₅₈	BR	6
91133 1998 HK ₁₅₁	BR	4	1999 CB ₁₁₉	RR	3
91205 1998 US ₄₃	BR	3	1999 CF ₁₁₉	BR	3
91554 1999 RZ ₂₁₅	IR-RR	3	1999 CX ₁₃₁	RR	3
95626 2002 GZ ₃₂	BR	6	1999 HS ₁₁	RR	3
118228 1996 TQ ₆₆	RR	4	1999 OE ₄	RR	3
118379 1999 HC ₁₂	BR	3	1999 OJ ₄	RR	3
119070 2001 KP ₇₇	IR	3	1999 OM ₄	RR	3
121725 1999 XX ₁₄₃	RR	3	1999 RB ₂₁₆	IR-BR	3
129772 1999 HR ₁₁	RR-IR	3	1999 RX ₂₁₄	RR	3
134340 Pluto	BR	3	1999 RE ₂₁₅	RR	3
134860 2000 OJ ₆₇	RR	6	1999 RY ₂₁₄	BR	3
136108 2003 EL ₆₁	BB	6	2000 CL ₁₀₄	RR	3
136199 Eris	BB	6	2000 GP ₁₈₃	BR	3
1993 FW	IR	3	2000 OK ₆₇	RR	6
1993 RO	IR	3	2000 PE ₃₀	BB	6
1995 HM ₅	BR	3	2001 CZ ₃₁	BB-	6
1995 WY ₂	RR-IR	3	2001 KA ₇₇	RR	3
1996 RQ ₂₀	IR-RR	3	2001 KD ₇₇	RR	3
1996 RR ₂₀	RR	3	2001 QF ₂₉₈	BB	6
1996 TK ₆₆	RR	3	2001 QY ₂₉₇	BR	3
1996 TS ₆₆	RR	5	2001 UQ ₁₈	RR	3
1997 QH ₄	RR	3	2002 DH ₅	BR	3
1998 KG ₆₂	RR-IR	3	2002 GF ₃₂	RR	3
1998 UR ₄₃	BR	3	2002 GJ ₃₂	RR	3
1998 WT ₃₁	BB	3	2002 GV ₃₂	RR	3
1998 WU ₂₄	BR	4	2003 AZ ₈₄	BB	6
1998 WS ₃₁	BR	3			

over, we classified with the same algorithm 134340 Pluto and 55638 (2002 VE₉₅). In Table 4 we report the resulting classification for 135 objects with the indication of the number of variables used in classifying each object. Some uncertainties (double or nonassignment) remain for only eight objects, but the appartenance to a given group has to always be considered with some caution because it is only an indication when it is obtained with an incomplete dataset. One of these objects is not classified at all. This fact suggests that other groups could be found if the number of objects analyzed will increase and therefore the proposed taxonomy can still be refined.

The average values of six broadband colors obtained for each class and the relative error bars are represented in Fig. 2 as reflectances normalized to the Sun and to the V colors

$$R_{c_\lambda} = 10^{\pm 0.4(c_\lambda - c_{\lambda_0})}$$

where c_λ and c_{λ_0} are the λ -V colors of the object and of the Sun respectively.

To analyze the behavior of the four TNO taxons with respect to the orbital elements, we calculate the distributions of the TNO taxons with respect to (1) their semima-

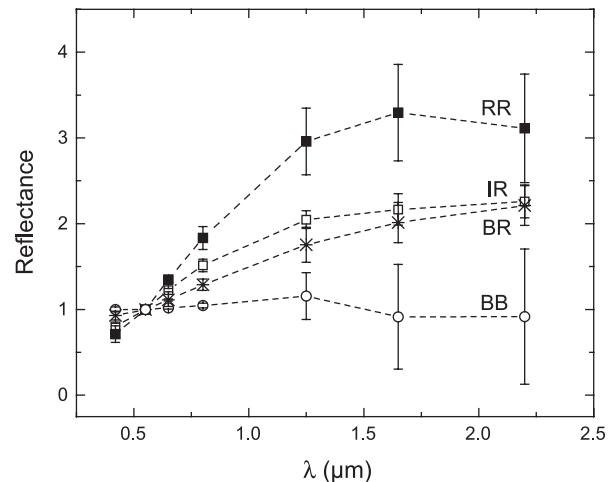


Fig. 2. Average values of the reflectance of the six broadband colors obtained for each taxon normalized to the Sun and to the V colors.

major axis and (2) their inclination. In Fig. 3 the percentage of objects belonging to a given taxon is reported vs. the semimajor axis (Fig. 3a) and the inclination of their orbits (Fig. 3b) respectively.

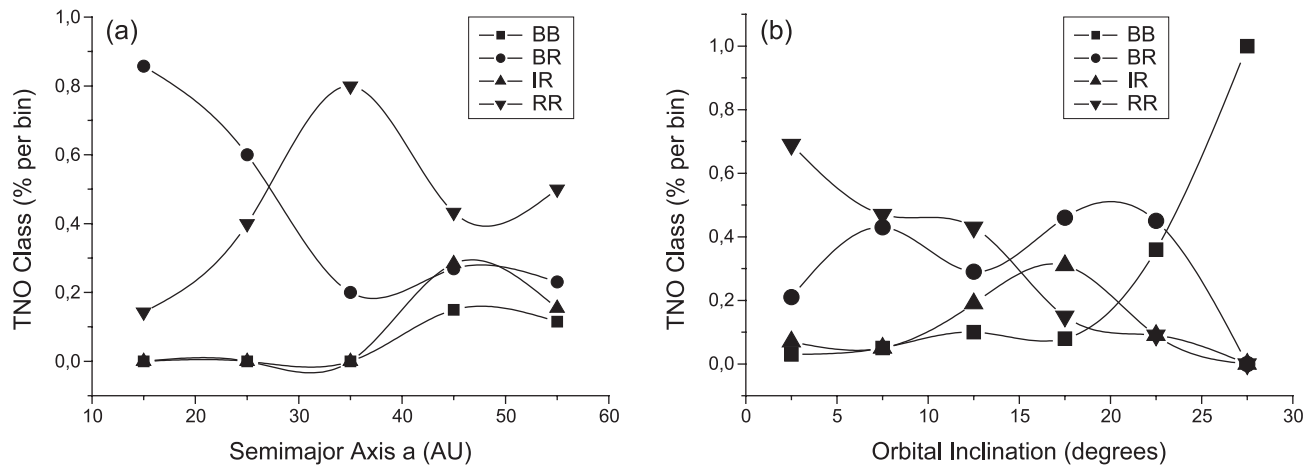


Fig. 3. Percent of objects belonging to a given class vs. (a) the semimajor axis and (b) the inclination of their orbits.

The following indications can be extracted by these distributions: (1) Centaurs belong to the BR group (the larger number) or to the RR taxons, confirming the known color bimodality of that object (Tegler and Romanishin, 1998, Peixinho et al., 2003); the TNOs are distributed in all the taxons, but a larger number of classical objects belongs to the RR taxon. (2) The more distant objects are quite equally subdivided in all the four taxons. (3) The orbital inclinations of the RR TNOs are in general low, confirming the fact that these objects are primordial objects (cold population) with low-inclination orbits, while the high-inclination objects belong to the BB taxon, which seems to be the representative of the “hot” population (Levison and Stern, 2001; Brown, 2001; Doressoundiram et al., 2002; Gomes, 2003; chapter by Doressoundiram et al.). (4) The taxon BR spans the entire range of inclinations, while the taxon IR is characterized by intermediate inclinations (15°–20°).

Moreover, in Fig. 4 the distribution of the different taxons within each TNO dynamical class is shown. The bimodality of the Centaurs is evident, the objects classified as

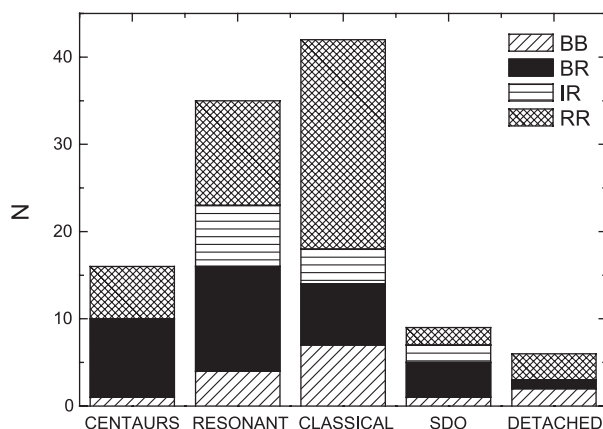


Fig. 4. Distribution of the different taxons within each TNOs’ dynamical class.

IR seem to be concentrate in the resonant and classical dynamical classes, while the RR objects dominate the classical dynamical class.

5. CONCLUSIONS

We applied two multivariate statistical methods (PC analysis and G-mode analysis) to a sample of 67 TNOs and Centaurs for which a homogeneous set of four colors (B–V, V–R, V–I, and V–J) are available. The results provided a quasi-continuous trend from neutral to very red spectra. The results of the G-mode analysis allowed us to distinguish a finer structure superimposed on this trend, separating four groups of homogeneous objects and one single-class object, confirming the results obtained by Barucci et al. (2005a), which analyzed 51 objects described by the same variables.

Analyzing a subsample of 55 objects for which a fifth and a sixth variable (the V–H and V–K colors) are available, the same four groups are confirmed. The significance level (99%) of this grouping is larger than (93%) obtained by Barucci et al. (1987) in classifying a sample of 438 asteroids with the same statistical techniques. This represents a strong indication that colors reveal real differences in the surface nature of the TNOs, probably having originated through their physico-chemical evolution.

A classification of TNOs and Centaurs based on their broadband colors has been proposed by Barucci et al. (2005a) using a two-letter designation for each taxon (BB, BR, IR, and RR). Such classification gives a good indication about the resemblances and/or differences among objects.

Using the extended version of the G-mode analysis for those objects with only three colors (B–V, V–R, and V–I), we obtain a preliminary classification of another 66 objects (for a total of 135 objects). Among these, one object remains unclassified, and seven have double classification. The availability of at least a fourth variable (V–J or V–H or V–K) appears to be essential for good statistical applications.

The behavior of each group with respect to the orbital elements shows that the RR object inclinations are low and those of the BB objects are high, while BR and IR taxons have inclinations spanning the entire inclination range. The Centaurs exhibit a clear bimodality: Most of them belong to the BR or RR taxon (see chapter by Tegler et al.).

We can conclude that the multivariate analysis of broadband spectrophotometric data of TNOs provides indications for differences in the surface nature of these objects. The quasicontinuous trend, demonstrated by the principal component analysis, is probably a witness to the possible sequence of the alteration processes undergone by the surface of each object, while the different taxons, obtained with G-mode analysis, indicate the present physico-chemical state of the analyzed objects.

It is possible to interpret these results both in terms of evolution of the TNO population and/or in terms of original differences in the composition of the objects. Several scenarios are possible and the lack of fundamental data (albedo, size, mass and size distributions, etc.) make it very difficult to develop a quantitative model describing the history of the TNO population. Here we propose two simple scenarios to provide some clues for interpreting the behavior of the TNOs.

In terms of evolution, we can consider that (1) the position of an object along the trend connecting the BB taxon to the RR taxon would indicate the time during which it has been exposed to the different alteration processes (e.g., activity, collisions, cratering, energetic particle bombardment), starting from a given initial state (original or consequence of a resetting event); (2) each taxon represents a different stage in the evolution of the population; (3) the relative number of objects in each group would account for how long that stage has lasted; and (4) the presence of single-object groups may imply the existence of different (cyclic?) evolution paths.

In terms of original compositional differences, we can conclude, following Gomes (2003), that the “hot” population is composed by the objects having quite high orbital inclinations and belonging to the BB taxon, while the “cold” indigenous population is that represented by the RR objects, some of which seem to contain very pristine compounds, such as methanol ice. The intermediate BR and IR taxons would represent the results of the aging of the surfaces of the BB and RR objects respectively, due to the exposure to the environmental modifying processes. The energetic particle bombardment of “dirty” icy surfaces induces the formation of dark, redder hydrocarbon coating films, which could be considered to be responsible for the BB → BR transition. A “rain” of micrometeorites over long time intervals may cause the loss of volatiles on the surface of the RR objects and change the characteristics of the overlying ices, which would result in the objects being less red than they were previously: RR → IR. Rejuvenation processes (energetic collisions, degassing activity) can reset most of the surface of an affected object to its initial condition, ac-

tivating a cyclic change in the surface color properties and consequently their classification.

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