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COLORS OF INNER DISK CLASSICAL KUIPER BELT OBJECTS

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ABSTRACT

We present new optical broadband colors, obtained with the Keck 1 and Vatican Advanced Technology telescopes, for six objects in the inner classical Kuiper Belt. Objects in the inner classical Kuiper Belt are of interest as they may represent the surviving members of the primordial Kuiper Belt that formed interior to the current position of the 3:2 resonance with Neptune, the current position of the plutinos, or, alternatively, they may be objects formed at a different heliocentric distance that were then moved to their present locations. The six new colors, combined with four previously published, show that the ten inner belt objects with known colors form a neutral clump and a reddish clump in $B-R$ color. Nonparametric statistical tests show no significant difference between the $B-R$ color distribution of the inner disk objects compared to the color distributions of Centaurs, plutinos, or scattered disk objects. However, the $B-R$ color distribution of the inner classical Kuiper Belt Objects *does* differ significantly from the distribution of colors in the cold (low inclination) main classical Kuiper Belt. The cold main classical objects are predominately red, while the inner classical belt objects are a mixture of neutral and red. The color difference may reveal the existence of a gradient in the composition and/or surface processing history in the primordial Kuiper Belt, or indicate that the inner disk objects are not dynamically analogous to the cold main classical belt objects.

Key words: Kuiper Belt: general

1. INTRODUCTION

Ongoing discovery and orbital and physical characterization of Kuiper Belt Objects (KBOs) and related outer solar system bodies promise new insight into the formation and evolution of our solar system. However, the evolving dynamical picture shows that the orbits of many, if not most, objects have been substantially changed over time. Thus, it may be difficult to study any differences between objects that formed at different heliocentric distances, as the current heliocentric distances of individual objects may differ radically from the heliocentric distances at the time of their formation.

Gomes (2003) hypothesized a dynamical mechanism to move the dynamically hot (high values of orbital inclination (i) and eccentricity (e)) KBOs from a massive protoplanetary disk truncated at 30–35 AU from the Sun outward to the present Kuiper Belt region. This mechanism would not work for the cold KBO population (low values of orbital inclination (i) and eccentricity (e); Morbidelli et al. 2008). In the Gomes model, the cold KBO population would either have formed in situ or would have been moved by a different mechanism. In the context of the Nice model of the outer solar system, a mechanism has been proposed that could move even cold KBO objects from a disk truncated at ~35 AU to their present distances (Levison et al. 2008). In this model, the dynamically cold KBO objects would have formed in the outer regions of the massive protoplanetary disk, perhaps in the region around 30 AU.

The vast majority of the known dynamically cold classical belt objects have semimajor axes (a) between 42 and 48 AU. There are also low e, low i classical objects with $a < 39.4$ AU. This semimajor axis is less than the current position of the Neptune 3:2 resonance, the semimajor axis at which Pluto and the plutino KBOs are currently found. The population of these objects, known as inner classical belt KBOs (ICKBOs), with a between about 36 and 39.4 AU, is much lower than that of the main classical belt objects (a between 42 and 48 AU). Because of the relative dearth of known classical belt objects interior to the Neptune 3:2 resonance, no published physical studies have specifically targeted these objects. This class of objects extends the a range of objects compared to the a range spanned by the main belt alone. Thus, it is potentially useful in the study of any gradients of chemical or surface processing history with formation distance for minor bodies in the outer solar system. Here we present new optical colors of a sample of inner classical KBOs. We compare the color distribution of these objects with that of other classes of outer solar system objects.

2. THE INNER CLASSICAL KUIPER BELT

A dynamical classification scheme for minor bodies in the outer solar system is presented by Gladman et al. (2008, hereafter GMV). They define inner classical belt objects as those that have semimajor axes (a) less than 39.4 AU, are not Centaurs, are not scattered disk objects (SDOs), and are not in resonant orbits. As explained in GMV, the stable inner classical belt is not disconnected from the main classical belt, which contains objects on stable, non-resonant orbits with $a = 42$–48 AU.

GMV only classify objects that met certain criteria for having sufficient astrometry as of 2006 May. They list 17 as inner classical KBOs (hereafter ICKBOs) and over 250 main classical KBOs (hereafter MCKBOs). As more recent astrometry is available, we searched the continuously updated listing[5] of the Deep Ecliptic Survey (DES) team (Elliot et al. 2005) for possible ICKBOs in addition to those identified in GMV. We searched for objects with $a < 39.4$ AU which the DES team definitively classifies as "classical" objects based on their detailed orbital

[4] Observers at the Keck 1 and Vatican Advanced Technology telescopes.

[5] http://www.boulder.swri.edu/~buie/kbo/kbofollowup.html

integrations. Two additional members of the inner classical belt (144897 and 2003 QA92) were found in this way. Neither of these objects are classified in GMV.

Of the 17 ICKBOs identified in GMV, five are classified by the DES team as "scattered near" objects, rather than classical objects. All five of these objects have orbital inclinations over 10°. Thus, there is some disagreement over the classification of some objects in the $a < 39.4$ AU region. However, all but one of the objects for which colors are available have orbital inclinations less than 10°, and so are probably members of the inner classical belt. If we use the GMV classification, augmented by the two additional objects, the inner classical belt has 19 known objects. Kavelaars et al. (2009) estimate that the inner disk KBOs may have a population 10–20 times smaller than the main belt.

Evidence that the main classical Kuiper Belt is composed of a "cold" and "hot" population has been presented by Brown (2001). There is some evidence of differences in the physical properties between the cold and hot populations (see Peixinho et al. 2008, and references therein). However, the dividing line in inclination between the cold and hot populations is not sharp, and indeed a simple dividing line may not be useful, as the two populations may overlap. Brown (2001) models the two populations as separate Gaussians in inclination, with the cold population having $\sigma_c = 2\overset{\circ}{.}2$ and the hot having σ_h around 17°. Gulbis et al. (2006) use an inclination of about 5° to separate cold (core) and hot (halo) classical objects. However, Peixinho et al. (2008) find that the colors of classical main belt objects are uniformly red up to an inclination of 12°—that is, they do not see a break in colors at 5°.

Our initial goal was to measure the color of ICKBOs with the lowest values of i and e, as these could be an extension of the main cold classical belt toward the Sun. If this were the case, the inner objects would extend the semimajor axis range of the classical belt and provide a larger range of the semimajor axis in which to look for correlations between semimajor axis and physical properties than the a range provided by the main cold classical belt KBOs alone. However, new results on the structure of the Kuiper Belt obtained from surveys analyzed with observational biases taken into account (Kavelaars et al. 2009) indicate the possibility that the inner belt objects are not analogous to the cold main belt but are perhaps more analogous to the hot classical belt objects. Such hot objects originated at significantly different heliocentric distances compared to their present locations. Kavelaars et al. (2009) argue, from the number of expected and observed inner disk objects at low i, that the inner disk is most likely devoid of a cold component, but this conclusion is uncertain due to the small number of inner disk objects found so far in their survey.

In contradiction to the Kavelaars et al. (2009) results, Lykawka & Mukai (2007) specifically posit a *cold* inner disk. These authors state that cold classical KBOs are located in the inner disk region—37 AU $< a <$ 40 AU ($q <$ 37 AU)—as well as, of course, in the main belt region (42 AU $< a <$ 47.5 AU).

Thus, to summarize, the inner classical disk may be an extension of the cold main classical belt, or it may be a hotter component that will not tell us directly about any changes in physical properties as a function of formation radius in the cold population. To the extent that optical colors can be related to formation radii, colors of inner objects might give a hint as to the origin of this population. More definite dynamical information on the origin of the inner objects must await a larger sample of objects. Also, careful modeling of the observational biases must be taken into account (Kavelaars et al. 2009) to specify whether the ICKBOs are part of a dynamically hot or cold population.

3. OBSERVATIONS

BVR imaging observations of five ICKBOs were obtained with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck 1 telescope on Mauna Kea on 2006 September 20. We operated LRIS in its dual-channel imaging mode that allows simultaneous imaging in a blue and a red channel. We took 300 s images through a B (438 nm) filter on the blue side, and alternated between a V (547 nm) and an R (642 nm) filter on the red side, with a dichroic element (D460) separating incoming light into blue and red channels.

There were some very intermittent light clouds during our observations. Repeatability of magnitudes in the B images indicates that the clouds attenuated light by no more than a few tenths of a magnitude at worst. Clouds are almost true neutral absorbers in the optical region (Serkowski 1970; Honeycutt 1971), with $B-V$ and $V-R$ colors made bluer by no more than 0.01 mag for 1 mag of extinction. Thanks to the dual-channel imaging operation mode, our colors should not be affected to any significant extent by the presence of these thin clouds. Observations of Landolt standard stars (Landolt 1992) were used to derive color transformation equations to the Johnson–Kron–Cousins system, as in our previous observations with this instrument (Tegler & Romanishin 2003). Nine high-quality standard stars from three Landolt fields (SA 110, PG 2213−006, and SA 95) were used to derive transformation equations between instrumental and system colors. These transformation equations were indistinguishable, within errors, to those shown in Tegler & Romanishin (2003). The solar color in this system is $B-R =$ 0.99 (Peixinho et al. 2008).

New colors of 119951 reported here were obtained with B (450 nm), V (550 nm), and R (650 nm) glass filters in front of a 2048×2048 pixel CCD camera at the $f/9$ aplanatic Gregorian focus of the 1.8 m Vatican Advanced Technology Telescope (VATT; the Alice P. Lennon telescope and Thomas J. Bannan facility) on Mount Graham, Arizona. We binned the 15 μm pixels 2×2, yielding 1024×1024 pixels, covering $6\overset{\prime}{.}4 \times 6\overset{\prime}{.}4$ of the sky at $0\overset{\prime\prime}{.}375$ pixel^{-1}. Observations of 119951 were obtained on 2005 June 7, during a five-night run of photometric weather. Multiple observations of 16 stars in three Landolt fields (PG 1633+099, PG 1323−086, and SA 110) were used to derive transformation equations. The scatter of the individual colors of the standard stars with respect to the equation was typically less than 0.01 mag.

Results of the new observations are reported in Table 1. The first column gives the name of the object, if one has been assigned, otherwise the provisional designation is listed. The second column gives the permanent number of the object, if one has been assigned. Other columns give the optical BVR colors and the error in the color (σ is the dispersion in the individual color measurements and n is the number of independent measurements). V magnitudes are quoted to only a tenth of a magnitude, as thin clouds may have affected these measurements. Also, the time span over which each object was observed was between 1 and 2 hr, not long enough to get a proper rotational magnitude sampling for objects with substantial lightcurve variations. The last three columns give the semimajor axis (a), eccentricity (e), and inclination (i).

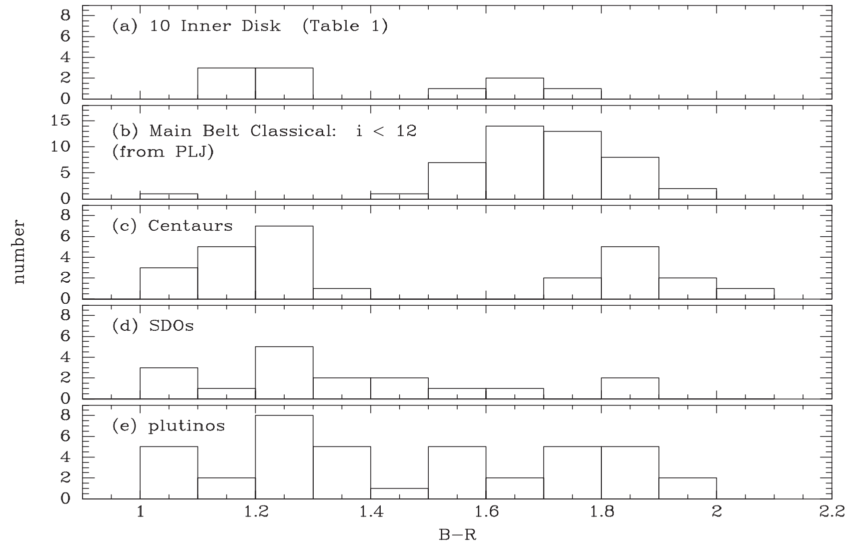

Figure 1. Histograms of $B-R$ colors of ten inner Kuiper Belt Objects and samples of other classes of objects as discussed in the text.

Table 1
New and Existing Colors for Inner Disk Objects

Object	Number	$B-R$	$\frac{\sigma}{\sqrt{n}}$	$B-V$	$\frac{\sigma}{\sqrt{n}}$	$V-R$	$\frac{\sigma}{\sqrt{n}}$	V	a	e	i
Previously unpublished colors											
2001 QT322[a]	135182	1.24	0.06	0.71	0.06	0.53	0.12	23.9	37.1	0.017	1.8
2002 KX14[b]	119951	1.66	0.04	1.05	0.03	0.61	0.02	20.88	39.0	0.042	0.4
2003 QA92[a]		1.67	0.02	1.04	0.03	0.63	0.04	22.7	38.0	0.061	3.4
2003 QQ91[a]		1.18	0.05	0.67	0.06	0.51	0.08	24.0	38.7	0.074	5.4
2003 YL179[a]		1.26	0.09	0.81	0.04	0.45	0.10	23.8	38.9	0.005	2.5
2004 UX10[a]	144897	1.53	0.02	0.95	0.02	0.58	0.03	20.9	38.9	0.039	9.5
Previously published colors											
1998 SN165[c]	35671	1.16	0.12	0.71	0.10	0.44	0.08		38.2	0.042	4.6
1998 WV24[d]		1.27	0.03	0.77	0.01	0.50	0.03		39.2	0.044	1.5
Rhadamanthus[c]	38083	1.18	0.11	0.65	0.09	0.53	0.07		38.8	0.155	12.8
1999 OJ4[c]		1.77	0.17	1.10	0.16	0.67	0.07		38.2	0.028	4.0

Notes.
[a] Observed with Keck 1 telescope 2006 Sep 20.
[b] Observed with VATT 2005 Jun 7.
[c] http://www.eso.org/~ohainaut/MBOSS/
[d] Tegler & Romanishin (2000).

We also searched for previously published colors of ICKBOs, primarily using the MBOSS online database[6] (Hainaut & Delsanti 2002). Four additional objects were found, and for convenience their *BVR* colors are listed in Table 1.

Although the sample of ten colors seems small, it is about half of the total known population of ICKBOs. The remaining objects are small and mostly very faint, and will require significant time on very large telescopes to obtain good colors. A histogram of the $B-R$ colors of the objects in Table 1 is shown in Figure 1.

4. COLORS OF INNER DISK OBJECTS

The histogram of $B-R$ colors for the ICKBOs shown in Figure 1 certainly suggests the possibility of a bimodal color distribution. However, the "dip test" (Hartigan 1985; Peixinho et al. 2003) does not indicate a statistically significant bimodal signal for the present sample (50% rejection of unimodal hypothesis). The "dip test" may, in a sense, be too restrictive when the question is whether or not two classes of objects are present. It *is* possible to combine two distinct classes of objects and get a combined distribution with a *single* mode (Zhu 2007). The definitive discussion of unimodality or bimodality of the inner disk object colors must wait until a larger sample of colors is available.

We use two different nonparametric or distribution-free statistical tests to compare the $B-R$ color distributions of ICKBOs with samples of other classes of outer solar system objects. The Wilcoxon rank-sum test, also known as the Mann–Whitney test, calculates the probability that two populations have the same mean, so could arise from the same parent population (Alder & Roessler 1977; Langley 1971). This test compares the sum of the rankings of the values of the individual samples in a pooled, ordered union of the two samples. The test is useful for comparing samples which are not distributed normally, as the test requires no assumption of normal or Gaussian distributed populations. We also use the more familiar Kolmogorov–Smirnov (or K-S) test (Press et al. 2007). We use implementations of these tests found in the statistical package *R*.[7]

6 http://www.eso.org/~ohainaut/MBOSS/

7 http://www.R-project.org

We first compare the $B-R$ colors of the ten ICKBOs with $B-R$ colors to samples of 26 Centaurs and 17 SDOs from Tegler et al. (2008). Next we compare the ICKBO sample to the sample of 41 plutinos with $B-R$ colors (Romanishin & Tegler 2007). Histograms of the $B-R$ colors of the samples of Centaurs, SDOs, and plutinos used are shown in Figure 1. The Wilcoxon test shows that the probability that the distributions of ten ICKBOs and the 26 Centaurs have the same mean color is 90%. For the ICKBOs and the plutinos the probability is 36%, and for the ICKBOs and the SDOs the probability is 80%. Thus, we find no evidence of any statistically significant difference between the average color of ICKBO and Centaur or SDO $B-R$ color distributions. While there is a greater difference between the ICKBO and the plutino $B-R$ color distributions, it is only at the 1σ level and so it is not statistically significant.

If the inner objects are an extension of the cold main belt population, then any difference in color distribution could indicate a radial gradient in physical properties. As discussed earlier, an alternative view is that the inner disk objects are not part of the cold classical disk. If this is so, the objects we have studied are just the low i and e members of a broader inclination distribution akin to the hot main belt objects. Main belt KBOs, particularly those that have low e and i, are very predominately red (Tegler & Romanishin 2000; Trujillo & Brown 2002; Doressoundiram et al. 2002), with $B-R$ colors typically around 1.7. From the results of Peixinho et al. (2008, hereafter PLJ), we first use $B-R$ colors of objects up to i of 12° as the cold main belt population distribution to compare to the ICKBO colors.

Our first comparison is between the $B-R$ colors of the ten objects in Table 1 and the 46 objects from PLJ with i up to 12°. The Wilcoxon test shows that the probability that the distributions of $B-R$ colors of ten ICKBOs and the 46 objects from PLJ have the same average color is 0.1%. The K-S two-sample test applied to the same samples also indicates the probability that the distributions of $B-R$ colors of ten ICKBOs and the 46 objects from PLJ have the same average color is 0.1%.

Next we restrict the samples to $i < 5^\circ$, as several groups propose this as a boundary between cold and hot classical populations (Gulbis et al. 2006; Noll et al. 2008). This leaves seven objects from Table 1 and 34 objects from PLJ. The Wilcoxon test shows that the probability that the distributions of the seven ICKBOs and the 34 objects from PLJ have the same average color is 1%. The K-S two-sample test applied to the same samples indicates probability that the distributions of seven ICKBOs and the 34 objects from PLJ have the same average color is 2%. The decrease in sample size of the $i < 5^\circ$ samples presumably accounts for the slight increase in probability for the smaller samples.

5. DISCUSSION

When we began this particular project, we thought that the low e and i inner belt objects were a natural sunward extension of the cold classical population found between $42 < a < 48$ AU at low e and i. Our original aim was simply to measure colors for a sample of these objects to compare the colors with the cold main belt objects. As discussed in Section 2, the dynamical status of the low e, i inner disk objects is a major question. The importance of these objects is only now being recognized; for example, the Nice model of Levison et al. (2008) said nothing specifically about the inner classical disk.

Much as we would like to have a definite answer to the precise relationship between the inner-classical KBOs and the cold-classical KBOs, neither our color data nor the dynamical models can resolve this issue at present. One of the main issues is the dynamical origin of the inner classical objects, as discussed in Section 2 above. So long as this issue remains unsettled, we are left with admittedly frustrating result of two different possible "conclusions" for how our colors may relate these objects to the other populations. Though of course more color data are always welcome and could perhaps provide a stronger statement about the connection, or lack of connection, with the plutino population, that will have to wait for further discoveries of brighter inner classical objects amenable to measuring colors. In the meanwhile, we await further developments from the dynamicists to propose a possible resolution to this dilemma.

6. CONCLUSIONS

The $B-R$ color distribution of a sample of ten inner disk KBOs is shown to be not inconsistent with the color distribution of samples of plutinos, Centaurs, and SDOs. The current inner disk sample has both red and neutral colored objects, reminiscent of the Centaurs, which have a bimodal $B-R$ color distribution. However, we cannot claim that the ICKBOs have a statistically significant bimodal signal with the present data.

The average $B-R$ color of the ICKBOs is inconsistent, at the 98% level or higher, depending on specific sample and statistical test used, with the colors of a sample of cold (low inclination) classical KBOs with semimajor axes between 42 and 48 AU. Possible conclusions of this are as follows.

1. The inner disk objects we observed, even though they are of low e and i, are members of a population analogous to the *hot* classical KBOs. The hot classical KBOs do not show a predominately red optical color distribution, as do the cold classical objects.
2. If the inner disk objects are in fact members of a cold inner disk population which is a sunward continuation of the cold classical objects between 42 and 48 AU, then there is a radial color gradient in the colors of this cold disk population of KBOs.

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REFERENCES

Alder, H. L., & Roessler, E. B. 1977, Introduction to Probability and Statistics (6th ed.; San Francisco, CA: Freeman)
Brown, M. E. 2001, AJ, 121, 2804
Doressoundiram, A., Peixinho, N., De Bergh, C., Fornasier, S., Thebault, P., Barucci, M. A., & Veillet, C. 2002, AJ, 124, 2279
Elliot, J. L., et al. 2005, AJ, 129, 1117
Gladman, B., Marsden, B. G., & VanLaerhoven, C. 2008, in The Solar System Beyond Neptune, ed. M. A. Barucci et al. (Tucson, AZ: Univ. Arizona Press), 43
Gomes, R. S. 2003, Icarus, 161, 404
Gulbis, A. A. S., Elliot, J. L., & Kane, J. F. 2006, Icarus, 183, 168
Hainaut, O. R., & Delsanti, A. C. 2002, A&A, 389, 641
Hartigan, P. M. 1985, Appl. Stat., 34, 320

Honeycutt, R. K. 1971, PASP, 83, 502
Kavelaars, J. J., et al. 2009, AJ, 137, 4917
Landolt, A. U. 1992, AJ, 104, 340
Langley, R. 1971, Practical Statistics (2nd ed.; New York: Dover)
Levison, H. F., Morbidelli, A., VanLaerhoven, C., Gomes, R., & Tsiganis, K. 2008, Icarus, 196, 258
Lykawka, P. S., & Mukai, T. 2007, Icarus, 189, 213
Morbidelli, A., Levison, H. F., & Gomes, R. 2008, in The Solar System Beyond Neptune, ed. M. A. Barucci et al. (Tucson, AZ: Univ. Arizona Press), 275
Noll, K. S., Grundy, W. M., Stephens, D. C., Levison, H. F., & Kern, S. D. 2008, Icarus, 194, 758
Oke, J. B., et al. 1995, PASP, 107, 375
Peixinho, N., Doressoundiram, A., Delsanti, A., Boehnhardt, H., Barucci, M. A., & Belskaya, I. 2003, A&A, 410, L29
Peixinho, N., Lacerda, P., & Jewitt, D. 2008, AJ, 136, 1837
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 2007, Numerical Recipes: The Art of Scientific Computing (Cambridge: Cambridge Univ. Press), 736
Romanishin, W., & Tegler, S. C. 2007, in ASP Conf. Ser. 371, Statistical Challenges in Modern Astronomy IV, ed. G. J. Babu & E. D. Feigelson (San Francisco, CA: ASP), 210
Serkowski, K. 1970, PASP, 82, 908
Tegler, S. C., Bauer, J. M., Romanishin, W., & Peixinho, N. 2008, in The Solar System Beyond Neptune, ed. M. A. Barucci et al. (Tucson, AZ: Univ. Arizona Press), 105
Tegler, S. C., & Romanishin, W. 2000, Nature, 407, 979
Tegler, S. C., & Romanishin, W. 2003, Icarus, 161, 181
Trujillo, C. A., & Brown, M. E. 2002, ApJ, 566, L125
Zhu, Z. 2007, in ASP Conf. Ser. 371, Statistical Challenges in Modern Astronomy IV, ed. G. J. Babu & E. D. Feigelson (San Francisco, CA: ASP), 220