A Collisional Family in the Classical Kuiper Belt

E. I. Chiang

Center for Integrative Planetary Sciences
Astronomy Department
University of California at Berkeley
Berkeley, CA 94720, USA
echiang@astron.berkeley.edu

ABSTRACT

The dynamical evolution of Classical Kuiper Belt Objects (CKBOs) divides into two parts, according to the secular theory of test particle orbits. The first part is a forced oscillation driven by the planets, while the second part is a free oscillation whose amplitude is determined by the initial orbit of the test particle. We extract the free orbital inclinations and free orbital eccentricities from the osculating elements of 125 known CKBOs. The free inclinations of 32 CKBOs strongly cluster about 2° at orbital semi-major axes between 44 and 45 AU. We propose that these objects comprise a collisional family, the first so identified in the Kuiper Belt. Members of this family are plausibly the fragments of an ancient parent body having a minimum diameter of ∼800 km. This body was disrupted upon colliding with a comparably sized object, and generated ejecta having similar free inclinations. Our candidate family is dynamically akin to a sub-family of Koronis asteroids located at semi-major axes less than 2.91 AU; both families exhibit a wider range in free eccentricity than in free inclination, implying that the relative velocity between parent and projectile prior to impact lay mostly in the invariable plane of the solar system. We urge more discoveries of new CKBOs to test the reality of our candidate family and physical studies of candidate family members to probe the heretofore unseen interior of a massive, primitive planetesimal.

Subject headings: Kuiper Belt — comets: general — minor planets, asteroids — celestial mechanics

1. INTRODUCTION

According to linear secular theory, the inclination, \( i \), and longitude of ascending node, \( \Omega \), of the orbit of a test particle embedded in a planetary system evolve with time, \( t \), as
\[
p \equiv i \sin \Omega = \sum_{i=1}^{N} A_i \sin(f_i t + \gamma_i) + i_{\text{free}} \sin(B t + \gamma_{\text{free}}) \quad (1)
\]

\[
q \equiv i \cos \Omega = \sum_{i=1}^{N} A_i \cos(f_i t + \gamma_i) + i_{\text{free}} \cos(B t + \gamma_{\text{free}}) \quad (2)
\]

[see, e.g., Chapter 7 of Murray & Dermott (1999)]. Here \(f_i\) and \(\gamma_i\) are functions of the masses, orbital semi-major axes, inclinations, and nodes of the planets; \(A_i\) depends on these same quantities and the semi-major axis of the particle; and \(B\) is given by the planetary masses and orbital semi-major axes of the planets and of the particle. The number of eigenmodes describing the forced vertical motion equals \(N\) and is usually equal to the number of planets in the system. The “free” or “proper” inclination, \(i_{\text{free}}\), and \(\gamma_{\text{free}}\) are constants specified by the initial \(i\) and \(\Omega\). Analogous equations exist for the test particle’s eccentricity, \(e\), and longitude of periastron, \(\dot{\omega}\).

Hirayama (1918) noted that certain asteroids share similar values of \(i_{\text{free}}, e_{\text{free}}, \) and semi-major axis, \(a\). He termed these groups “families,” and christened the first three families Koronis, Eos, and Themis using the names of their respective first-discovered members. A family’s members are thought to be fragments of a collisionally disrupted parent body. Immediately following the disruption event, each fragment is characterized by osculating orbital elements \(a_0 + \delta a, e_0 + \delta e\), and \(i_0 + \delta i\), where the subscript 0 pertains to the parent body just prior to disruption. Fragments for which \(\delta a/a_0, \delta e/e_0, \delta i/i_0 \ll 1\) have nearly the same \(i_{\text{free}}\) and \(e_{\text{free}}\). A non-zero \(\delta a\) induces a change in the free precession frequency, \(\delta B\). As the orbits of fragments differentially precess in their nodes and apses, their osculating \(i\)’s and \(e\)’s may span wide ranges, particularly if the magnitude of the forced term is close to that of the free term. However, the constants of integration, \(i_{\text{free}}\) and \(e_{\text{free}}\), will remain fixed barring non-secular effects (e.g., close encounters with planets, or mean-motion resonant effects), effectively recording the inceptive shattering event.

Classical Kuiper Belt Objects [CKBOs; see, e.g., the reviews by Jewitt & Luu (2000), Farinella & Davis (2000), and Malhotra, Duncan, & Levison (2000)], which we define to be those bodies having orbital semi-major axes between 43 and 47 AU, currently do not reside within low-order mean-motion resonances with the giant planets. Secular theory well describes the dynamical evolution of CKBOs on low-\(e\), Neptune-avoiding orbits, modulo the effects of weak chaos (Torbett 1989; Torbett & Smoluchowski 1990; Duncan, Levison, & Budd 1995). Here we report on an elementary calculation of the free inclinations and
free eccentricities of known CKBOs. We uncover evidence for the first collisional family in trans-Neptunian space. The candidate family is dynamically reminiscent of a sub-family of the Koronis population in the asteroid belt. Section 2 describes our computational method, and section 3 contains results and discussion.

2. METHOD

Osculating elements of CKBOs were downloaded from the Minor Planet Center (MPC; http://cfa-www.harvard.edu/iau/lists/TNOs.html). We selected only those objects observed at multiple apparitions and having fitted semi-major axes $43 < a (\text{AU}) < 47$. See Millis et al. (2002) for a discussion of how orbital uncertainties depend on the arclength of astrometric observations. The resultant list contained 125 CKBOs.

For each CKBO having an observed $p_{\text{obs}} \equiv i_{\text{obs}} \sin \Omega_{\text{obs}}$ and $q_{\text{obs}} \equiv i_{\text{obs}} \cos \Omega_{\text{obs}}$, we compute

$$i_{\text{free}} = \sqrt{(p_{\text{obs}} - p_{\text{forced}})^2 + (q_{\text{obs}} - q_{\text{forced}})^2}$$

and similarly for $e_{\text{free}}$. To evaluate the forced terms, we employ the secular theory of Brouwer & van Woerkom (1950; hereafter BvK) for all eight planets of the solar system, as transcribed by Murray & Dermott (1999). Now the osculating elements of KBOs given by the MPC pertain to epochs between 1994 and 2002 A.D., and are referred to the ecliptic and equinox of J2000. Since the BvK solution defines $t = 0$ to be 1900 A.D., we take $t = 100$ yrs in equations (1) and (2) and ignore the small, 8-year spread in MPC epochs. Since the BvK solution refers to the ecliptic and equinox of B1950, we transform the MPC orbital angles $(i, \Omega, \bar{\omega})$ to the B1950 frame using formulae provided by Montenbruck (1989, pages 18–19). Differences between untransformed and transformed angles are no more than $1^\circ$. We note also typographical errors in the transcription of the BvK solution by Murray & Dermott (1999); in their captions for Tables 7.2 and 7.3, $e_{ij}$ and $I_{ij}$ should instead read $e_{ji}$ and $I_{ji}$, respectively, in keeping with their notation throughout the rest of chapter 7 (subscript $j$ denotes the planet, while subscript $i$ denotes the eigenmode).

Our method for extracting proper elements is crude compared with modern techniques. We neglect terms higher than degree 2 in planetary eccentricities and inclinations; see Milani & Knežević (1994) to remedy this deficiency. We retain only terms that are linear in the eccentricity and inclination of the CKBO, forsaking the semi-numerical approach of Williams (1969) and more recent, purely numerical approaches (Knežević and Milani 2001) that avoid expansions of the test particle’s orbit altogether. Thus, we cannot expect accuracy in our
results for highly inclined and eccentric CKBOs. Nonetheless, many observed CKBOs execute nearly circular and co-planar trajectories for which we expect the errors introduced by our analysis to be small. And for simplicity and ease of implementation, our procedure is probably bested only by Hirayama’s celebrated and successful (1918) analysis, which included only a truncated Jovian secular potential \[N = 1\] in equations (1) and (2). It is in his pioneering spirit that we search for the first collisional family in the Kuiper Belt.

3. RESULTS AND DISCUSSION

Figure 1 displays the inclinations and eccentricities, observed and free, of CKBOs against their semi-major axes. While the observed elements betray no obvious clumping, this is not true for the free inclinations. We consider the population of KBOs having \[44 \lesssim a (\text{AU}) \lesssim 45\] and \[1 \lesssim i_{\text{free}} (\text{deg}) \lesssim 3\] to be a candidate collisional family. Table 1 provides the designations, semi-major axes, free elements, and \(H\)-magnitude inferred diameters of our 32 candidate family members.

The free inclinations of our candidate family cluster about \(2^\circ\), similar to the inclination of the invariable plane with respect to the ecliptic, \(i_{\text{invar}}\). This coincidence might lead one to suspect that these bodies represent primordial ones that coagulated in the invariable plane, rather than fragments generated by catastrophic disruption. In this alternative scenario, these bodies would appear in \(p-q\) space at the point representing the inclination and node of the invariable plane referred to the ecliptic. Would all such bodies share the same \(i_{\text{free}}\), without recourse to collisional genesis? There are two ways by which they might do so, but both paths are prohibitive. The first way is if \(i_{\text{forced}} \ll i_{\text{free}}\) (see Figure 7.3 in Murray & Dermott), so that \(i_{\text{free}} \approx i_{\text{invar}}\). The former condition fails to be satisfied; for every one of our candidate members, \(i_{\text{forced}} \approx i_{\text{free}}\). The second option demands that all bodies appear in \(p-q\) space over a timescale much shorter than the local forced precession timescale of \(\sim 2\pi/f_8 \approx 2 \times 10^5 \text{yr}\). In this case, the forced inclination vectors of bodies appearing in \(p-q\) space would be nearly identical since there would be insufficient time for the forced vectors to rotate. There would be differences in the amplitudes of the forced inclination vectors from body to body, but these would be small since \(\Delta a/a\) is small for our candidate family and the bodies are far from secular resonances. Consequently, the free inclination vectors of all bodies appearing at a single point in \(p-q\) space would be nearly the same. However, for all members of our candidate family to have formed well within a time interval of \(2 \times 10^5 \text{yr}\) seems unreasonable. Current planetesimal coagulation calculations indicate KBO growth times of order \(10^7 \text{yr}\) (Kenyon 2002, and references therein). By contrast, a collisional disruption event is virtually instantaneous; we proceed under the hypothesis of a collisional origin for
Our candidate family boundaries were chosen based on visual inspection of Figure 1c and the remarkable narrowing of the distribution of inclinations between panels 1a and 1c exhibited by our candidate family. A Kolmogorov-Smirnov (K-S) test comparing the distributions of observed and free inclinations for our candidate family yields a 0.1% probability that the two distributions are drawn from the same underlying distribution. We consider this probability sufficiently low that we believe the narrowing of the inclination distribution to be significant. No other subset of KBOs in Figure 1 evinces the same degree of sharpening when we transform from observed to free elements; we compute corresponding K-S probabilities of ∼20% for other subsets of KBOs.

Comparing the distribution of free inclinations of our candidate family to that of 22 KBOs having $43 \lesssim a(\text{AU}) \lesssim 44$ and $1 \lesssim i_{\text{free}}(\text{deg}) \lesssim 4$ reveals no significant difference; the K-S test yields a 38% probability that the two distributions are drawn from the same population. A comparison between our candidate family and the 12 KBOs having $45 \lesssim a(\text{AU}) \lesssim 46$ and $1 \lesssim i_{\text{free}}(\text{deg}) \lesssim 3$ gives a corresponding probability of 13%, again too high to claim a significant difference. Thus, our family, if real, might extend over the full gamut of semi-major axes from 43 to 46 AU. Subjectivity in the choice of family boundaries is a problem that afflicts even the relatively mature field of asteroidal dynamics, and clearly more objects would be desirable. We defer more sophisticated analyses of the significance of the clumping in $i_{\text{free}}$-$a$ space to future study. For the present, we reserve our attention to the 32 KBOs between $a = 44$AU and 45 AU that exhibit the sharpest concentration of free inclinations.

The free eccentricities of our candidate family are more broadly distributed than their free inclinations. This characteristic is reminiscent of the Koronis asteroid sub-family located at semi-major axes $2.84 \lesssim a(\text{AU}) \lesssim 2.91$. This sub-family exhibits an absolute width of ∼0.025 in $e_{\text{free}}$ and an absolute width of ∼0.005 in $\sin i_{\text{free}}$ (Bottke et al. 2001). The corresponding widths for our candidate Kuiper Belt family are 0.15 and 0.03, respectively. That these widths are each ∼6 times greater than their Koronis sub-family counterparts probably reflects the greater ease with which orbital trajectories are altered in the more distant Kuiper Belt; orbital velocities are ∼4 times lower in the CKB than in the asteroid belt.

\[ \text{The Koronis family divides into two groups ("sub-families"), one located at } 2.84 \lesssim a(\text{AU}) \lesssim 2.91 \text{ and a second located at } 2.92 \lesssim a(\text{AU}) \lesssim 2.95. \text{ The free eccentricities in the latter sub-family are markedly higher than those in the former, reflecting excitation via passage through a secular resonance located at } 2.92 \text{ AU (Bottke et al. 2001). The free eccentricities and free inclinations of the former sub-family are thought to be of collisional origin, and we employ this sub-family as the analogue of the Kuiper Belt family proposed here. Within the former Koronis sub-family, the spread in free eccentricities is still larger than the spread in free inclinations, and appears to demand an anisotropic distribution of ejecta velocities.} \]
Fig. 1.— (ab) Observed (osculating) inclinations and eccentricities of 125 multi-opposition CKBOs, as supplied by the Minor Planet Center on March 25, 2002. (cd) Free inclinations and eccentricities of these objects, as computed from observed values, using the secular theory of Brouwer & van Woerkom (1950) to subtract off forced contributions. Emboldened circles represent the 32 objects having $44 < a_{\text{AU}} < 45$ and $1 < i_{\text{free}}(\text{deg}) < 3$. The free inclinations cluster more strongly than the observed inclinations, pointing to a common, likely collisional origin for these objects. The spread in $e_{\text{free}}$ of our candidate family is larger than in $i_{\text{free}}$, similar to behavior exhibited by a sub-family of the Koronis asteroids.
The larger variation in $e_{\text{free}}$ compared to that in $i_{\text{free}}$ exhibited by both families presumably reflects a collision in which fragment ejecta velocities were greater in the (invariable) plane of the solar system than out of the plane. This, in turn, probably implicates a collision between two ancient bodies having greater relative velocity in the plane than out of the plane.

The mass of the projectile, $M_{\text{proj}}$, that shattered the parent body could not have been much smaller than that of the parent, $M_{\text{par}}$. For the kinetic energy of the collision (measured in the frame moving at the center-of-mass velocity) to exceed the gravitational binding energy of the parent body, $\min(M_{\text{proj}}/M_{\text{par}}) \sim (v_{\text{esc,par}}/v_{\text{rel}})^2$, where $v_{\text{esc,par}}$ is the escape velocity from the parent body and $v_{\text{rel}}$ is the relative velocity between projectile and target. Using the fragment sizes in Table 1 that are derived from an assumed albedo $A = 0.04$, we estimate the minimum diameter of the putative parent body to be $\sim 800\sqrt{0.04/A}$ km, for which $\min(v_{\text{esc,par}}) \sim 0.4\sqrt{0.04/A}$ km s$^{-1}$. The relative velocity must be a fraction, $f$, of the local orbital velocity: $v_{\text{rel}} \sim 1 (f/0.2)$ km s$^{-1}$. Thus, $\min(M_{\text{proj}}/M_{\text{par}}) \sim 0.2 (0.2/f)^2 (0.04/A)$.

Surface reflectance spectra of members of a dynamical family can lend supporting evidence for a common physical ancestry. The Koronis sub-family exhibits relatively homogeneous S-type optical colors that set it apart from the more variegated field population (e.g., Gradie, Chapman, & Williams 1979). The parent body for the Koronis family is thought to be $\sim 120$ km in diameter (Bottke et al. 2001), too small to have undergone significant internal differentiation. More massive parent bodies may have differentiated; collisional fragments from such bodies may display greater variation in their spectral properties. Thus, finding a large spread in optical colors among members of a given candidate family does not necessarily eliminate the candidate from the running; widely different colors and/or spectra may instead offer a glimpse into the shattered, chemically zoned interior of a minor planet.

Unfortunately, color photometry exists for only 3 of our 32 candidate family members (1999 CM119, 1999 HU11, and 1999 CO153) in Table 1. Their B-V and B-R colors are plotted in Figure 2, along with the available colors of all other CKBOs [we employ data from Trujillo & Brown (2002), selecting only those objects having $43 < a (\text{AU}) < 47$]. The tendency for the 3 candidate family members to be redder than those of the general Classical population (Figure 2a) may imply homogeneity of the interior of the putative parent body. Alternatively, it may reflect whatever unknown process is responsible for generating the color-inclination correlation reported by Trujillo & Brown (2002). In an attempt to separate out this effect, we plot only data for those CKBOs having $i_{\text{obs}} < 7^\circ$ in Figure 2b. There remains a tendency for our KBO family candidates to skirt only the lower envelope of the space spanned by all low-$i$ CKBOs, though clearly there are too few points and the uncertainties in individual points are too large to claim significant segregation. We urge physical studies of the candidate family members listed in Table 1 to further explore the possibility that we
Fig. 2.— (a) Optical colors of CKBOs. Only 3 of the 32 candidate family members in Table 1 have had their colors measured; they are symbolized by solid circles. (b) Same as (a), except that only colors of CKBOs having $i_{obs} < 7^\circ$ are plotted.
are indeed viewing the heretofore unseen interior of a massive, primitive planetesimal.

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Table 1. Candidate Kuiper Belt Family Members

| MPC Designation | a (AU) | $i_{\text{free}}$ (deg) | $e_{\text{free}}$ | Diameter\(^a\)(km) |
|-----------------|-------|-----------------------|------------------|-------------------|
| 2001 ES24       | 44.537| 2.49                  | 0.068            | 175               |
| 2001 DB106      | 44.101| 2.77                  | 0.124            | 332               |
| 2000 YV1        | 44.629| 1.99                  | 0.101            | 253               |
| 2000 PN30       | 44.632| 1.95                  | 0.097            | 160               |
| 2000 PY29       | 44.061| 1.27                  | 0.060            | 231               |
| 2000 GY146      | 44.044| 2.78                  | 0.027            | 175               |
| 2000 GX146      | 44.408| 2.01                  | 0.071            | 183               |
| 2000 GV146      | 44.290| 2.04                  | 0.102            | 201               |
| 2000 FR53       | 44.866| 1.98                  | 0.124            | 192               |
| 2000 FG8        | 44.224| 1.72                  | 0.049            | 183               |
| 2000 FC8        | 44.009| 2.13                  | 0.066            | 167               |
| 2000 FA8        | 44.003| 2.30                  | 0.023            | 210               |
| 2000 CH105      | 44.542| 2.64                  | 0.083            | 303               |
| 2000 CF105      | 44.191| 1.33                  | 0.050            | 277               |
| 2000 CE105      | 44.210| 1.15                  | 0.070            | 290               |
| 2000 CL104      | 44.673| 1.31                  | 0.087            | 381               |
| 1999 RA216      | 44.380| 2.05                  | 0.095            | 241               |
| 1999 RE215      | 44.940| 1.47                  | 0.109            | 317               |
| 1999 RC215      | 44.108| 2.43                  | 0.064            | 277               |
| 1999 OF4        | 44.760| 1.87                  | 0.060            | 277               |
| 1999 OZ3        | 44.019| 1.93                  | 0.137            | 220               |
| 1999 HU11\(^b\) | 44.025| 1.43                  | 0.053            | 303               |
| 1999 HS11       | 44.071| 1.09                  | 0.001            | 332               |
| 1999 DH8        | 44.387| 2.89                  | 0.071            | 122               |
| 1999 CU153      | 44.484| 2.05                  | 0.080            | 241               |
| 1999 CS153      | 44.794| 2.21                  | 0.119            | 160               |
| 1999 CO153\(^b\) | 44.008| 2.53                  | 0.094            | 220               |
| 1999 CN119      | 44.568| 2.16                  | 0.096            | 167               |
| 1999 CM119\(^b\) | 44.657| 1.44                  | 0.140            | 175               |
| 1999 CC119      | 44.680| 1.85                  | 0.009            | 253               |
| 1998 HM151      | 44.225| 1.29                  | 0.050            | 167               |
Table 1—Continued

| MPC Designation | a (AU) | $i_{\text{free}}$ (deg) | $e_{\text{free}}$ | Diameter$^a$(km) |
|-----------------|-------|-------------------------|------------------|-----------------|
| 1995 DC2        | 44.281| 2.23                    | 0.051            | 241             |

$^a$Based on an assumed albedo $A = 0.04$ and an absolute $H$-magnitude supplied by the Minor Planet Center.

$^b$B-V and B-R colors are available for these objects.