Dynamical Spreading of Asteroid Families via the Yarkovsky Effect

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ABSTRACT

The orbital distributions of prominent asteroid families are thought to be direct by-products of catastrophic disruption events among diameter $D > 100$ kilometer bodies. Ejection velocities derived from studying observed families, however, are surprisingly high compared to results from impact experiments and simulations. One way to resolve this apparent contradiction is by assuming that $D \lesssim 20$ kilometer family members, since their formation, have undergone semimajor axis drift via the thermal force called the Yarkovsky effect. Interactions between drifting family members and resonances can also produce unique eccentricity and/or inclination changes. Together, these outcomes help explain (i) why families are sharply bounded by nearby Kirkwood gaps, (ii) why some families have asymmetric shapes, and (iii) the curious presence of family members on short-lived orbits.

Catastrophic collisions among large asteroids in the main belt are believed to produce asteroid families (e.g., [1]), clusters of asteroid fragments with similar proper semimajor axes a, eccentricities e, and inclinations i [2] [3] and spectral signatures consistent with an origin from a common parent body [4]. As such, prominent asteroid families (e.g., Koronis, Eos, Themis, Eunomia, Vesta) are natural laboratories for understanding high velocity impact physics, one of the principal geologic processes affecting small bodies in the solar system.

Although this formation scenario is straightforward, there are still many aspects of asteroid families that we do not yet understand. We list a few below:

Velocity distributions. Up to now, the ejection velocities of observed asteroid family members have been derived under the assumption that the semimajor axes of these bodies have been relatively constant since the family was created [5] [6]. The diameter $D < 20$ km fragment velocities inferred from this technique are typically several 100 m s^{-1}. Curiously, these velocities are inconsistent with ejection velocities derived by other means. For example, numerical hydrocode experiments, which are capable of simulating hypervelocity collisions among large asteroids, indicate that mean ejection velocities of multi-km fragments from family-forming impacts are ~ 100 m s^{-1} [7] [8]. Although limited data is available to validate these codes on large-scale asteroid collisions, they have successfully reproduced results ranging from laboratory impact experiments, where cm-sized projectiles are shot into targets, to underground nuclear explosions (e.g., [7]).

Orbital distributions. Many prominent asteroid families have asymmetric and/or highly unusual (a, e, i) distributions [9]. As an example, we show the Koronis family in proper (a, e) and (a, i) (Fig. 1) [10]. Note that this family is nearly cut in two, with large proper a members more dispersed and actually offset in proper e than those with small proper a. In addition, both ends of the Koronis family are sharply bracketed by powerful mean motion resonances with Jupiter. Apparently, few observed family members have crossed either resonance, even though these resonances are relatively narrow when compared to the span of the family. This surprising coincidence cannot easily be explained in a simple scenario where the family's ejection velocity field has an upper cut-off.

EDITOR: PLACE FIGURE 1 HERE.

Family members on short-lived orbits. Several members of asteroid families are either "on the brink" of entering a resonance (e.g., Koronis family members; [11]), are already inside a powerful resonance (e.g., Eos family members; [12]), or are part of the relatively short-lived near-Earth object (NEO) population (V-type asteroids, which presumably were once part of the Vesta family before they escaped the main belt; [13]). Since the ages of families like Koronis, Eos, and Vesta are thought to be 1 Gy or more [14], it is difficult to understand how these family fugitives reached orbits with such short dynamical lifetimes ($\sim$ 10 My or less; [15] [16]).

These inconsistencies, and recent advances in our understanding of asteroid dynamics, have motivated us to consider a modified scenario for producing families: family members, rather than being static after ejection, instead undergo slow but steady migration via the Yarkovsky effect. The Yarkovsky effect is thermal radiation force which causes objects to undergo semimajor axis drift as a function of their size, spin, orbit, and material properties [17]. Analytical and numerical results show this force can move an ensemble of $D = 5$ km asteroids inward and outward at mean drift rates of $|da/dt| \sim 2 \times 10^{-5}$ AU My^{-1}, while larger asteroids drift more slowly (e.g., $D \sim 20$ km asteroids drift at $|da/dt| \sim 6 \times 10^{-6}$ AU My^{-1}) [18]. These rates, which are relatively insensitive to the surface properties of the asteroids in the size regime considered, are in the right ballpark to explain the observed semimajor axis dispersions of most asteroid families, particularly those which are hundreds of My to Gy old [14]. Moreover, because the magnitude of the Yarkovsky drift is size dependent, the final semimajor axis distribution depends on the size of the objects, as observed in [6].

To check our hypothesis, we tracked the dynamical evolution of Koronis family member using the symplectic integration code SWIFT-RMVS3 [19] modified to accommodate Yarkovsky thermal forces [17]. We concentrate on the Koronis family in this paper primarily because it exhibits all of the singular features described above and because its low (e, i) values keep it far from most potential interlopers. Our family formation model results are described step-by-step below.

Step 1–Catastrophic disruption. For our starting conditions, we assume the catastrophic disruption of the Koronis parent body ($D = 119$ km; [20]), arbitrarily placed at the orbit of (158) Koronis, ejected multi-km-sized fragments at velocities $\lesssim 60$ m s^{-1}. We purposely chose velocities lower than the inferred ejection velocities of observed Koronis family members ($\lesssim 300$ m s^{-1}; [6]) or even those of hydrocode simulations (~ 100 m s^{-1}; [8]) in order to gauge the importance of the Yarkovsky effect. For this reason, no attempt was made to match the (e, i) span of Koronis family values near, say, 2.87 AU, though more realistic initial conditions could readily do so. We tracked the evolution of 210 test asteroids with $2 < D < 40$ km. The test asteroids were given random spin axis orientations, spin periods between 4-12 h, and thermal and material properties consistent with regolith-covered asteroids like Koronis family member (243) Ida [21] [22].

Step 2–Dynamical evolution in semimajor axis. Our fragments were numerically integrated for ~ 700 My, less than the assumed age of the Koronis family (2.5-3.0 Gy [14] [21]) but long enough to determine evolutionary trends for slower-drifting bodies (Fig. 2). After 100 My, most bodies have migrated in semimajor axis alone; few significant changes in (e, i) are observed. Our largest fragments, being less susceptible to the Yarkovsky effect, do not move very far. We expect them to gain some limited mobility over the age of the family via processes like collisions and/or close encounters with asteroids like (1) Ceres, (2) Pallas, or (4) Vesta [23] [24].

EDITOR: PLACE FIGURE 2 HERE.

Step 3–Interactions with weak resonances. Yarkovsky forces drive many family members through numerous resonances where resonant jumping/trapping events produce noticeable changes in proper eccentricity, particularly on the right side of Fig. 2. The most conspicuous effects are not caused by chaotic diffusion, since the widths of the few mean motion resonances existing in this region are tiny at small e values. Rather, the dramatic jumps are caused by interactions with secular resonances (e.g., $g + 2g_5 - 3g_6$ at 2.92 AU) which increase e but do not significantly change i (Fig. 1) [25]. Note that if the Yarkovsky effect did not exist, asteroids injected into the $g + 2g_5 - 3g_6$ resonance would undergo cyclic e oscillations until removed from resonance by a collision or a close encounters with a large asteroid. With Yarkovsky, on the other hand, bodies drifting into the left separatrix increase their e values until reaching the right separatrix, where they can jump out of the resonance. This outcome gives Koronis family members passing through the $g + 2g_5 - 3g_6$ resonance a permanent boost in e. Ultimately, the Yarkovsky effect splits the Koronis family into two distinct "clouds" in (a, e) space, with those on the right side predominately comprised of small, fast-drifting objects (e.g., Fig. 1). Thus, the unusual (a, e) shape and size-orbit distribution of the Koronis family, together with the notable lack of dispersion in (a, i) space, provide strong evidence for asteroid mobility via the Yarkovsky effect.

Step 4–Interaction with strong resonances. Fig. 2 shows that Koronis family members drifting far enough within 700 My become trapped in the powerful 5:2 or 7:3 mean motion resonances. By definition, these objects, with $D \sim 2$ km and obliquities near 0° or 180°, have the fastest drift rates in our simulation. Despite this, none are seen to jump across the 5:2 or 7:3. Thus, resonance capture events explain why no concentrations of family members are observed on the left/right sides of the 5:2/7:3 resonances, respectively (Fig. 1). Once captured, Koronis family members are pushed onto planet-crossing orbits, where they go on to strike the Sun, a planet, or are ejected from the inner solar system by a close encounter with Jupiter (e.g., [16]).

We believe our simulation reproduces the overall (a, e, i) distribution, the apparent size sorting of the Koronis family, and the paucity of family members on the left/right sides of the 5:2 and 7:3 resonances, respectively, while also showing that some Koronis family members could be escaping out of powerful resonances today (i.e., Koronis member (2953) Vysheslavia, a 15 km body, is located so close to the 5:2 resonance that it will be ejected from the main belt within 10 to 20 My; [26]). Based on these results, we conclude that the Yarkovsky effect, working in concert with resonances, can explain the mismatch between the observed spread of asteroid families such as Koronis and the size-velocity distributions derived from hydrocode simulations, all within a consistent model. The drawback with this paradigm, unfortunately, is that the current orbital distributions of $D < 20$ km bodies among most asteroid families cannot be directly used to infer the properties of the original breakup.

Our results imply that some asteroids observed in the Mars-crossing and/or near-Earth regions were family members produced billions of years ago by catastrophic disruption events. Thus, since Yarkovsky drift rates are size-dependant, large near-Earth asteroids like (433) Eros could have taken billions of years to escape the main belt. This characteristic potentially explains why so few $D > 20$ km near-Earth asteroids exist and why (433) Eros has such a heavily-cratered surface.

Initially, the Yarkovsky effect was introduced into planetary dynamics as a possible transportation mechanism for meteorites. Today, we are beginning to recognize that the Yarkovsky effect, together with resonances, may be the dominant means by which

$D \lesssim 20$ km asteroids roam the main belt and reach the transportation resonances which can take them to the inner solar system (and Earth).

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[10] To distinguish the Koronis family from the background population, we applied a hierarchical clustering method (HCM) to the modern proper element database found at the AstDyS information system [3]. The criterion of family membership requires that all family members are connected by a "chain", where each member is located within a given velocity difference (cutoff) to its neighbor in proper (a, e, i). To be conservative, we have chosen 50 m s^{-1} as our cutoff velocity for family membership. Note that a larger cut-off velocity of 100 m s^{-1} increases the number of outliers but does not significantly change the shape of the orbital distribution, mainly because the background population near the Koronis family is sparse. We find that our new Koronis family has 1322 members with $1 < D < 46$ km $(8.7 < H < 16.5)$. Only a few objects near the lower D limit have been discovered. Our results are consistent with previous work [1].

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[25] Secular resonances are defined using precession rates: those of the body of interest (the longitude of perihelion g and longitude of node s) and those of various planets (e.g., g_6 and s_6 are the fundamental frequencies of Saturn, the 6th planet). The $g + 3g_5 - 3g_6 - g_7$ resonance at ~ 2.91 AU, the $g + 2g_5 - 3g_6$ at ~ 2.92 AU, and the $g + g_5 - 3g_6 - g_7$ resonance at ~ 2.93 AU are responsible for many of the "jumps" in e observed in Fig. 2. The jumps seen near 2.9 AU are associated with the 12:5 mean motion resonance with Jupiter and several overlapping secular resonances. The resonances responsible for the jumps at 2.89 AU have not yet been identified by our team, though they may be associated with various secular resonances and the weak 6:1 mean motion resonance with Saturn.

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Figure Captions

Fig. 1. Orbital distribution of 1322 Koronis family members (black dots) in proper semimajor axis a vs. proper eccentricity e and inclination i [10]. The grey dots are main belt asteroids having proper $e < 0.1$ and proper $\sin i < 0.05$. The family is bracketed by the 5:2 and 7:3 mean motion resonances with Jupiter. The left side of the 5:2 and the right side of the 7:3 show no significant concentrations of asteroids in both (a, e) and (a, i) space.

Fig. 2. Evolution of 210 simulated Koronis family members via the Yarkovsky effect. The test family members (blue lines) were started within ~ 60 m s^{-1} of (158) Koronis (proper elements $a = 2.87$ AU, $e = .045$, $\sin i = .038$) and were integrated for ~ 700 My, short compared with the estimated age of the family (~ 2.5 Gy) but enough to determine evolution trends. The orbital tracks were averaged over a running 10 My window in order to compare them with the proper (a, e) of the Koronis family members (gold dots). Snapshots of the integration tracks, shown at 100 Myr, 300 Myr, and 700 Myr, indicate these bodies interact with several resonances between 2.89–2.93 AU [25], with the secular $g + 2g_5 - 3g_6$ resonance at 2.92 AU being most prominent. These jumps allow the simulated family members to reach the (a, e) positions of many real family members. Fast-drifting bodies are seen to escape the main belt via the 5:2 and 7:3 mean motion resonances with Jupiter.

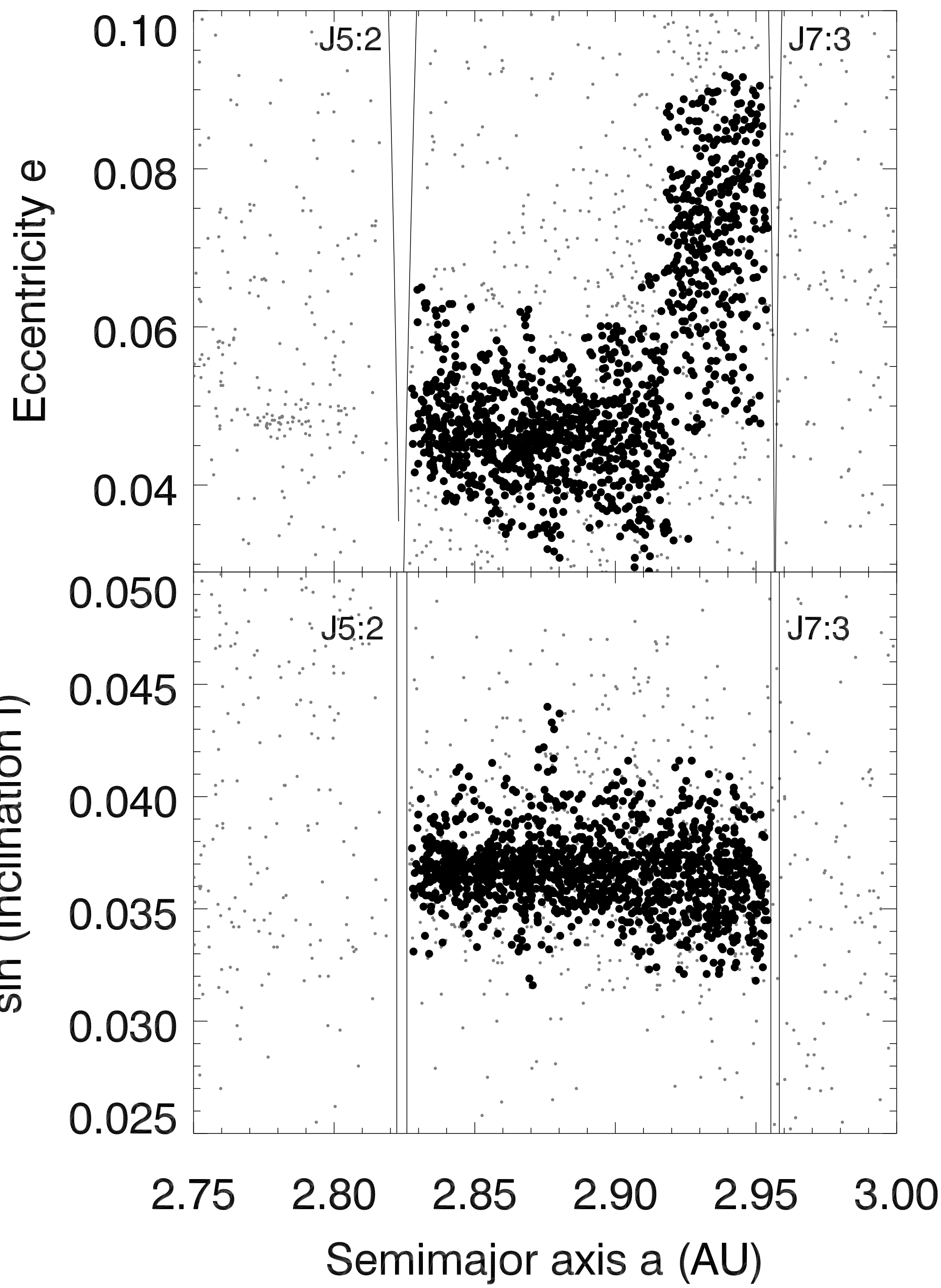
J5:2
J7:3
Eccentricity e
0.10
0.08
0.06
0.04
J5:2
J7:3
sin (Inclination i)
0.050
0.045
0.040
0.035
0.030
0.025
2.75
2.80
2.85
2.90
2.95
3.00
Semimajor axis a (AU)

Fig. 1.—

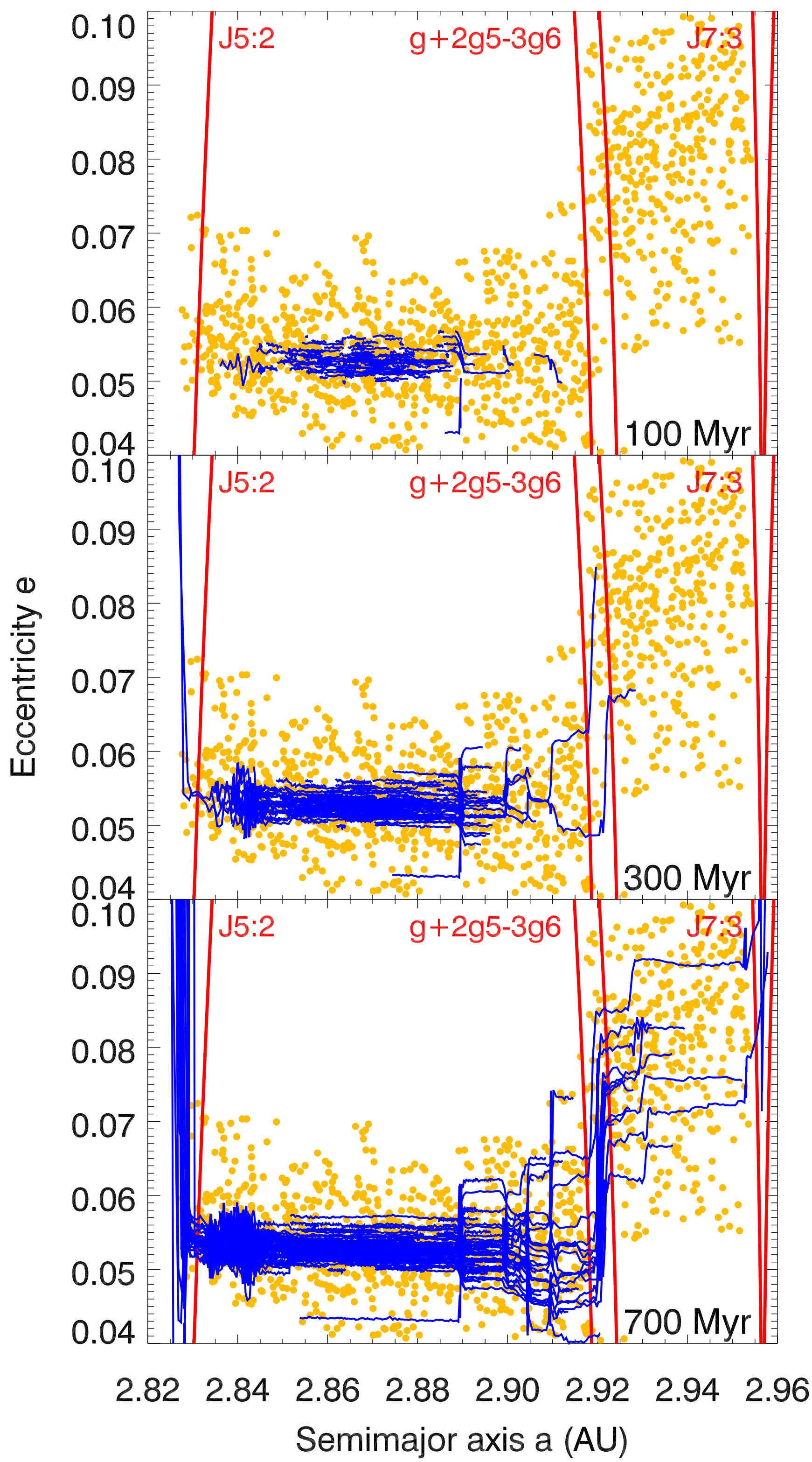
J5:2
g+2g5-3g6
J7:3
100 Myr
300 Myr
700 Myr
Eccentricity e
Semimajor axis a (AU)
0.10
0.09
0.08
0.07
0.06
0.05
0.04
2.82
2.84
2.86
2.88
2.90
2.92
2.94
2.96

Fig. 2.—