Long–term Dynamical Diffusion in Asteroid Families via the Yarkovsky Effect

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Motivating problem: Asteroid families are remnants of large–scale catastrophic collisions. They are usually identified by their proper orbital elements, which tend to be clustered at similar values. We wish to point out, and later address, two potential problems related to their origin and dynamical evolution.

- Proper orbital elements are frequently used to identify asteroid families. In general, they are assumed to be constants of motion. In practice, however, they are only tested over a few Myrs (i.e., the proper e and sin(i) computed by modern algorithms typically change by < 0.0015 over this timespan). In contrast, collisional models suggest that many prominent asteroid families are hundred of Myrs to Gyrs old. The large difference between these timescales makes it plausible to think that today's families may not be good images of families at their birth.
- Studies of the asteroid families suggest that most family fragments were collisionally ejected at high velocities, with the smallest fragments traveling the furthest from the cluster–center. Curiously, these high velocities have yet to be reproduced in numerical hydrocodes, which have otherwise been validated using laboratory experiments and underground nuclear explosions. Whenever high velocities are obtained in hydrocode models, the fragment distribution is dominated by small — and thus unobservable — fragments. For these reasons, hydrocodes have been considered unreliable tools for modeling the large impact events.

A plausible solution: We suggest that an alternative scenario might resolve these problems. Let us assume that ejection velocities derived from laboratory experiments and hydrocodes also apply to asteroid families. Thus, immediately after the break-up event, the fragments are thrown a short distance away from the target. At that point, we assume that some dynamical process dynamically disperses the family members over long timescales (say, hundreds of Myr to several Gyr). If that were the case, the distribution of asteroid families should be diagnostic of the processes producing asteroid mobility and the nature of the dynamical environment surrounding the target body. In fact, if we can understand the mobility processes well enough, we can use the current distribution of asteroid families to estimate the formation time of the family.

We claim that the unknown asteroid mobility mechanism is the Yarkovsky thermal force, which causes $D < 20$ km bodies to slowly drift inward/outward in semimajor axis. The drift rate is size-dependent, such that km–sized family members tend to move faster than multi–km bodies. This effect disperses asteroid families over long time scales while also giving them the appearance that they were launched using a size–dependent velocity distribution. We believe this aspect of the Yarkovsky effect helped camouflage the true dispersion mechanism for many years. As the fragments evolve, they interact with high–order mean–motion and/or secular resonances with the planets, causing them to change their eccentricity and inclination values in very distinctive ways. These changes can often be reproduced in our simulations, and they provide considerable support for our hypothesis.

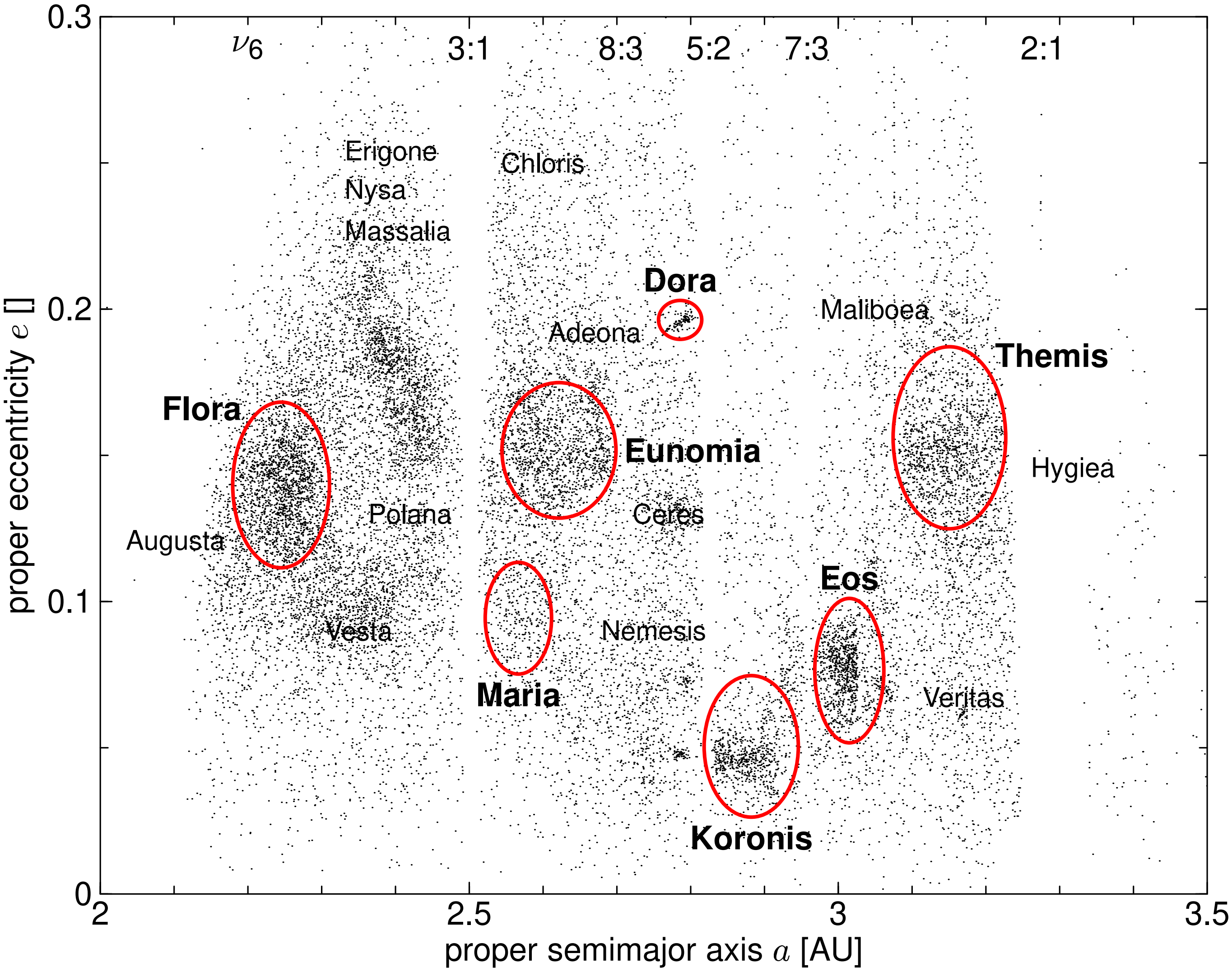
Method, integrator and selected families:

To study the problem we numerically integrated test asteroids using the SWIFT_RMVS3 code, which was modified to include both the diurnal and seasonal variants of the Yarkovsky effect. Symplecticity of the integrator was thus "weakly" broken, but several tests showed that the amount of the orbital energy dissipated by the Yarkovsky effect was small. Accordingly, the results of our procedure should be valid.

The test asteroids (210 per family) were placed at the assumed starting location (see page 3) and were then tracked for up to 500 Myr. Except for the case of Flora family, we considered perturbations by the outer planets only.

We have investigated 7 prominent asteroid families: **Flora, Maria, Eunomia, Dora, Koronis, Eos, Themis**. Many of these families have very different properties (young/old, compact/dispersed, far from/close to the principal mean motion resonances, etc.). Thus, each one has a unique story to tell.

Here we plot the selected families in the proper a vs. proper e projection:



Note: The results of the **Flora family** simulations are discussed separately by D. Nesvorný *et al.*: The Flora family: a case of the dynamically dispersed collisional swarm? (at session IV, Tuesday afternoon).

To complement, and better understand, our simulations, we have also integrated **the known members** of the Eos, Eunomia and Maria families (see pages 11–12).

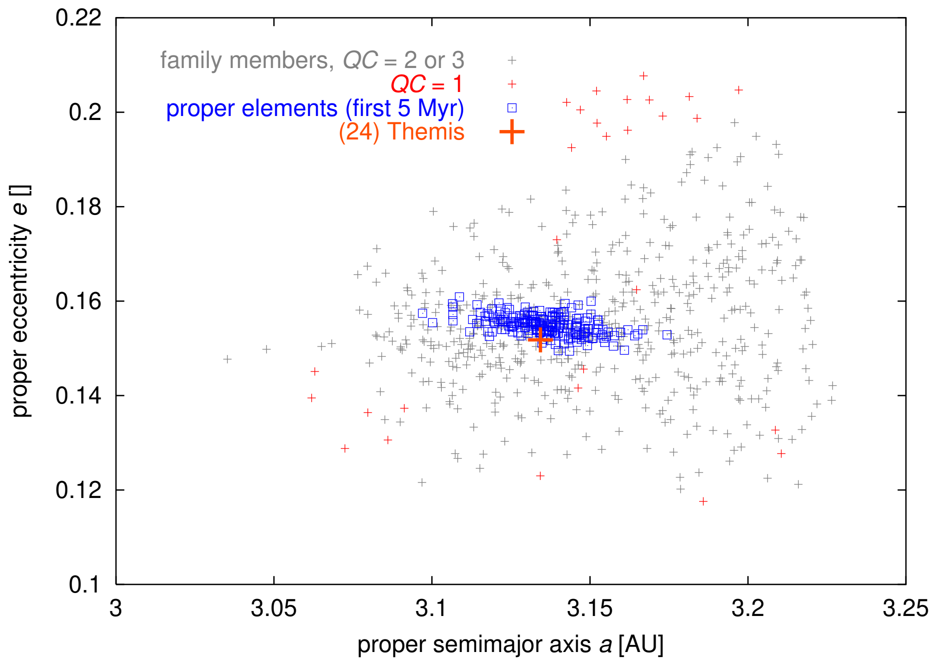
Initial conditions:

Motivated by our hypothesized scenario, we intentionally started our simulations with much more compact families than observed today. A brief outline of the procedure to generate the initial orbital data for each of the studied families is as follows:

- Since the Yarkovsky effect cannot disperse the largest members of the family, we assume the largest observed member to be close to the original disruption event (in the proper element space).
- From the observed size distribution of the family, we estimate the radius of the parent object and the specific energy for its disruption.
- We assume that the f_{KE} factor — determining how much of the disruption energy is deposited to the kinetic energy of the ejecta — is low (typically 0.01–0.05) such that family members are only moderately dispersed at the birth of the family.
- The ejecta are assumed to have Maxwellian velocity dispersion, with the mean ejection speed determined by the above given item and no mass dependence. We correct for the estimated escape velocity of the parent object to obtain velocities “at infinity” (i.e., after they escape from the potential describing their mutual attraction).
- We assume an isotropic velocity field created at particular instant along the parent body’s revolution around the Sun to get the appropriate skewness of the proper element distribution.

Our initial conditions are only approximate, but we believe they are reasonable enough to allow us to study effects of the long–term dynamical evolution in the family.

As an example, we show here the initial data for our simulation of the Themis family members (and compare them with the current positions of the observed members):



For each of the families, we generate **210 test–members**. We purposely choose smaller sizes for our test asteroids than the known family members so our numerical runs will finish within a reasonable amount of time. The smallest integrated objects have $R \approx 1$ km. Thermal parameters are estimated from the spectral type of the family. Low surface conductivity allows the diurnal variant of the Yarkovsky effect to dominate the seasonal variant. Hence, objects can drift both inward and outward. Rotation axes are initially randomized in space and are kept fixed during the simulation.

Conclusions:

1. Our numerical simulations suggest that family members evolve for hundreds of Myr to Gyr under the influence of the Yarkovsky effect. This evolution can reproduce many or most of the features of the observed asteroid families.
2. Most families look like they formed by collision ejection, where the smallest objects were given the highest velocities. Our simulations show that Yarkovsky evolution produces a similar result, since it is a size-dependent force.
3. Interactions with weak (or strong) mean motion resonances allow some family members to disperse in proper e and i. The match between our results and distribution of observed family members is reasonable for the current level of model sophistication.
4. Family members interacting with high–order secular resonances tend to evolve along the shape of the resonance. The paths these objects take frequently go through the orbital positions of observed family members. This interesting match suggests that asteroid mobility is needed to create the observed distributions of asteroid families.

Further work:

- Extend our simulations to longer timescales with more asteroids included.
- Include more realistic spin axis evolution (especially for small asteroids).
- Reanalyze the asteroid identification techniques with “a priori knowledge” of potentially on-going slow dynamical processes.

References and further reading:

A. Cellino: **HCM families file.** `http://www.to.astro.it/~cellino/`

A. Milani and Z. Knežević: Icarus **107**, 219 (1994)
→ on the theory of high–order secular resonances in the main asteroid belt

D. Nesvorný and A. Morbidelli: Astron. J. **116**, 3029 (1998)
→ on the role of weak mean motion resonances in the main asteroid belt

D. Vokrouhlický: Astron. Astrophys. **335**, 1093 (1998); *ibid.* **344**, 362 (1999)
→ on the Yarkovsky effect theory

P. Farinella and D. Vokrouhlický: Science **283**, 1507 (1999)
→ on the Yarkovsky effect role for small asteroids

D. P. Rubincam: Icarus **148**, 2 (2000)
→ on the YORP effect

D. Nesvorný *et al.*: **The Flora family: a case of the dynamically dispersed collisional swarm.** Icarus, submitted (2001)
→ results for the Flora family

- our web sites: `http://sirrah.troja.mff.cuni.cz/~mira/mp/`
  `http://www.boulder.swri.edu/~davidn/yarko/yarko.html`

Interactions between Yarkovsky–driven objects and resonances:

Objects evolving via the Yarkovsky effect frequently encounter and interact with resonance regions.

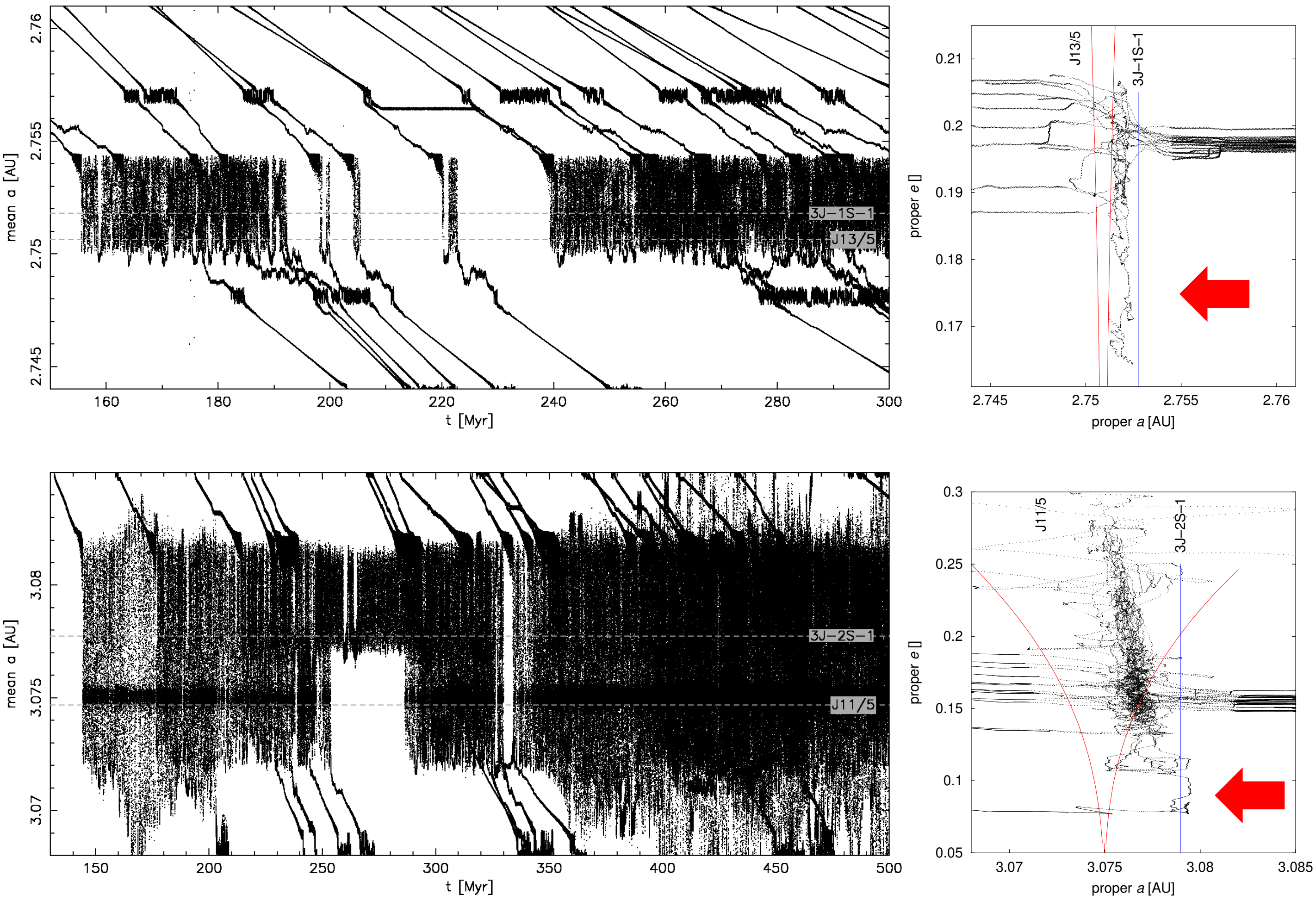
■ High–order mean–motion resonances:

Objects encountering a resonance will be trapped by it or will jump it altogether. Either way, the objects may undergo changes in the proper e and sin(i).

Here we show objects interacting with the J13/5 (and 3J–1S–1) resonances (Dora family) and the J11/5 (and 3J–2S–1) resonances (Themis family).

Mean a vs. time

Proper e vs. proper a



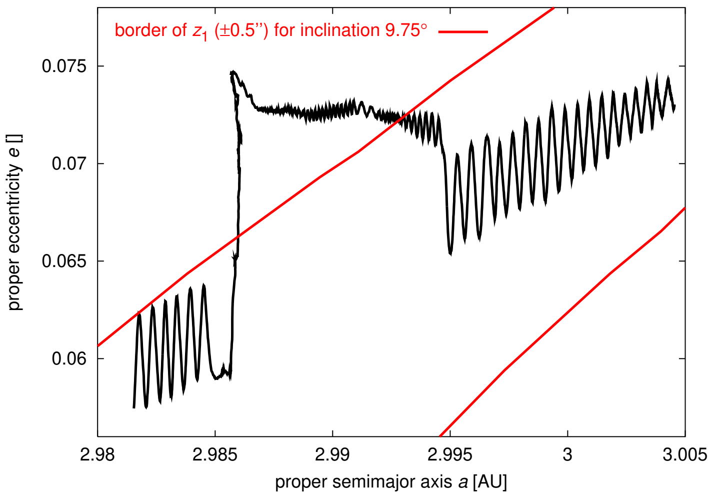
Note how proper eccentricities change as the bodies interact with the resonances. The red arrows indicate the drift direction.

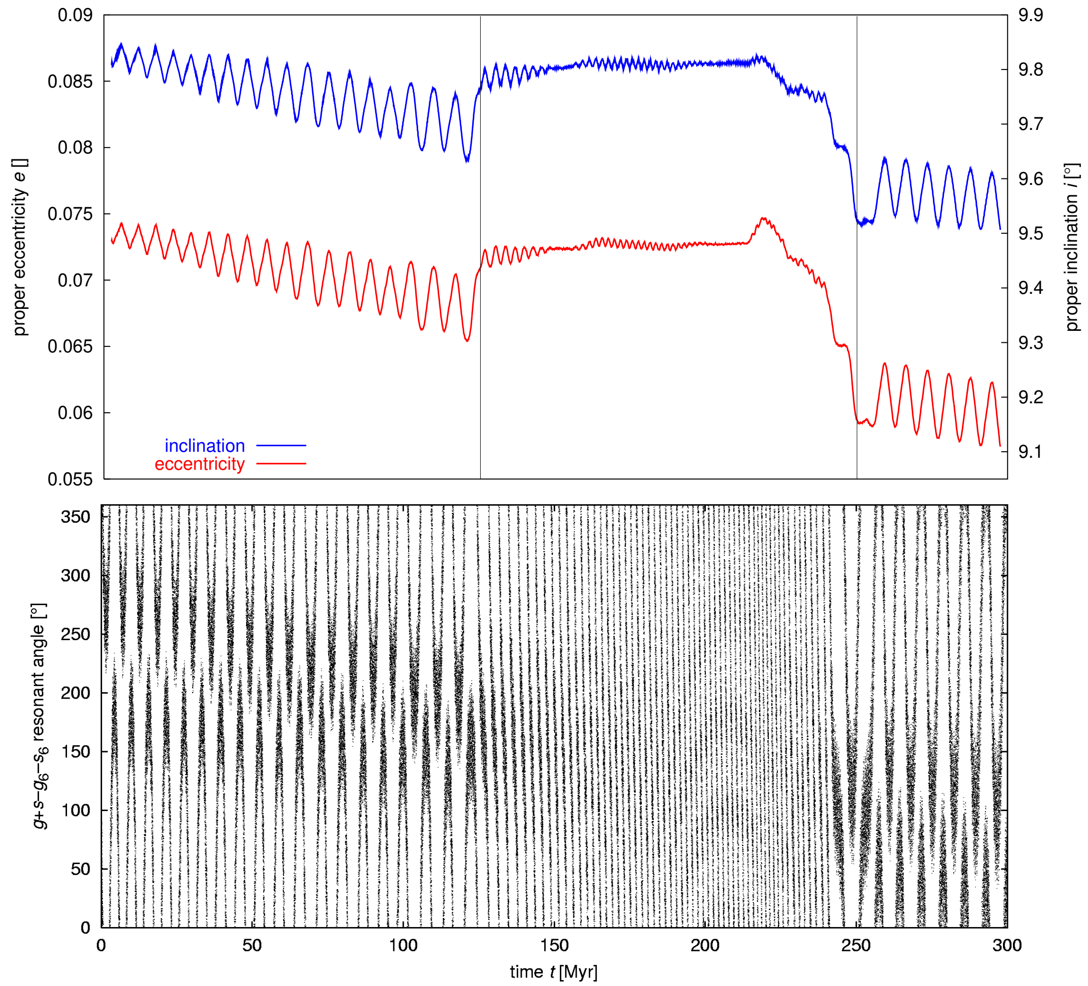
Interactions between Yarkovsky–driven objects and resonances:

■ High–order secular resonances:

Our objects also interact with high–order secular resonances. Though these resonances are not strong enough to cause major orbital instabilities, they can temporarily capture drifting objects and drive them into specific regions of the phase space. This behavior has been noticed for many families (e.g. Eos, Eunomia, Maria, Flora and Koronis).

Here we show the 300 Myr evolution of a potential Eos member orbit. The figure to the right shows proper a vs. proper e computed as 5 Myr filtered elements. The figures below show mean e and i as a function of time, and the critical angle of the $z_1 = g{+}s{-}g_6{-}s_6$ secular resonance. Librations of this quantity, and the large scale oscillations of the mean and "proper" elements, indicate periods when the orbit was captured in this resonance.



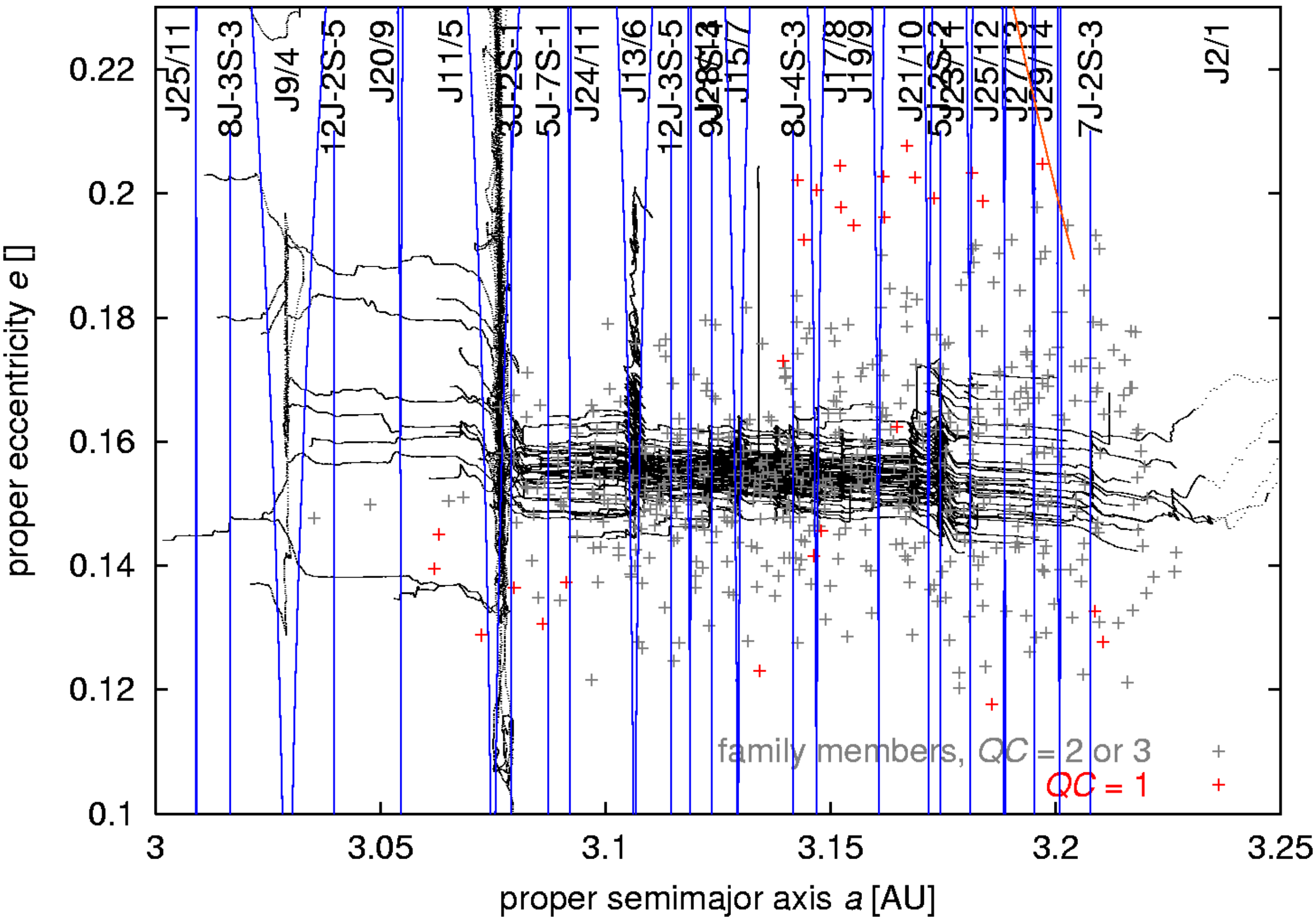


Themis:

The Themis family, with its large dispersion in proper (a, e, i), represents an important challenge/test for our scenario. Our initial data (see page 3) is tightly clustered near the location of the largest asteroids in the family. The Themis region, however, is located in the outer zone of the asteroid belt, which is characterized by a significant chaoticity due to numerous weak resonances (see the figure below). This may allow Yarkovsky–driven objects orbits to encounter enough resonances to attain the dispersion seen among the observed family members.

To test this hypothesis, we integrated 210 Themis (test) asteroids for 500 Myr. Below we show the corresponding evolution tracks, projected on the proper a vs proper e plane (the "proper" elements were computed as 5 Myr averages).

Two powerful resonances bracketing the Themis family are the J2/1 and J11/5 (together with 3J–2S–1) resonances. The former drives the asteroids out of the main belt, while the latter modifies proper e values enough that clustering techniques may no longer identify these objects as Themis family members. Many other weaker resonances slowly disperse the family as well (e.g. J13/6, 5J–2S–1, J25/12, 7J–2S–3, etc.).

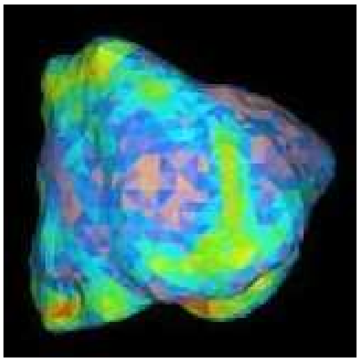


While our test asteroids do have their proper elements dispersed via interactions with resonances, our data does not yet reconstruct all features of the observed Themis family. We believe this may be due to the fact that (i) we are evolving objects for only a small fraction of the family age and (ii) for computational expediency, we are integrating objects which are smaller than the observed family members. If we were to integrate large objects, which have slower drift rates in a, it is plausible that interactions with small resonances may be more effective, such that we would get more dispersion in proper e and i. It is also possible that our model of the Yarkovsky effect is too simple, and that changes in the spin axes of the asteroids caused by Yarkovsky torque (so called YORP effect) need to be included.

Themis — continued:

The YORP torque is generically nonzero for irregularly shaped asteroids (such as Golevka on the right). This effect tilts the axis toward the orbital plane, or in the direction normal to the orbital plane, and in the same time decays the rotational energy. We have proven that a typical Themis asteroid would randomly reinitialize its rotation state (by mutual collisions) on a timescale $\approx 35\,R^2$ Myr, with R radius in km. For a 10 km–sized body this implies a reorientation time scale of ≈ 0.87 Gyr.

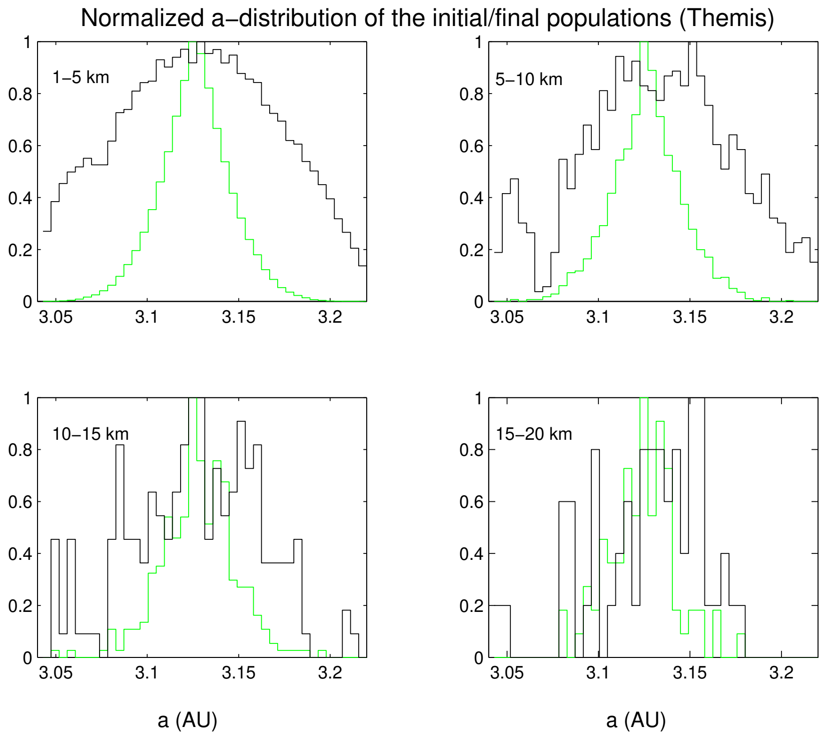
Note: We are currently running numerical simulation with the YORP effect included.

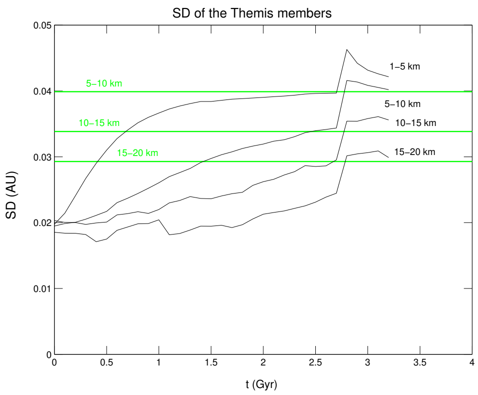


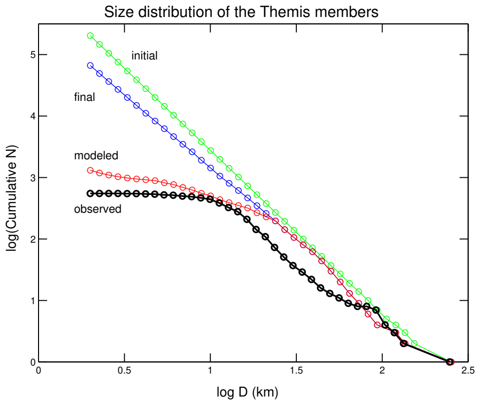
Another complexity of the extrapolation of our results to the whole family age is due to the so far omitted role of collisional disruptions. For young families (such as Flora, Dora and perhaps Eos) this approximation is not so critical, but it must be estimated for the old families.

Here we show results from a Monte Carlo code taking into account the semimajor axis mobility of the small asteroids together with their collisional evolution (though not in a fully self–consistent way; a similar approach was previously used for modelling the meteorite delivery toward the Earth). The interaction with the weak resonances, and their effect on proper e and i, are neglected in this approach. The following figures illustrate:

- initial/final dispersion of the family members in four size intervals;
- temporal evolution of the standard deviation of the proper a distribution (compared with the observed values in green);
- size distribution of the modeled population of the Themis asteroids – modeled means approximately corrected for the observational bias – and compared with the size distribution of the observed Themis members.

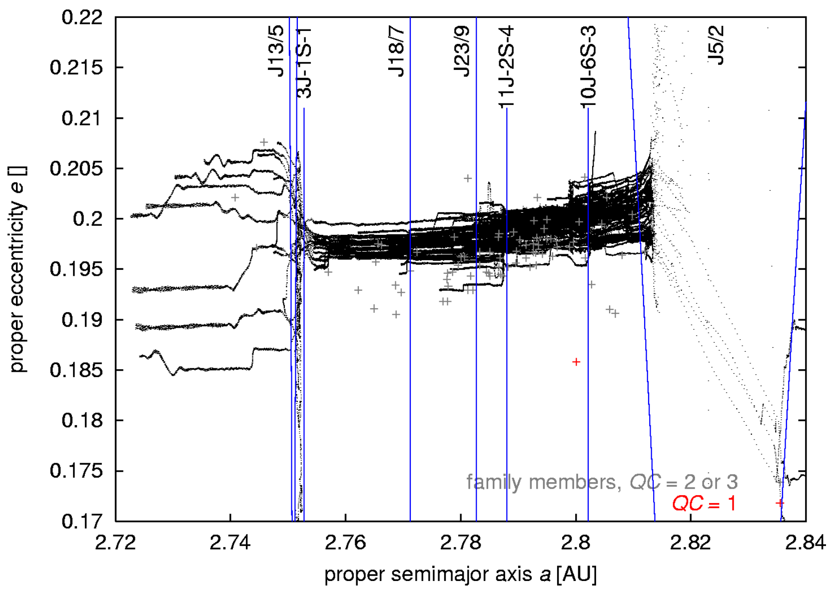






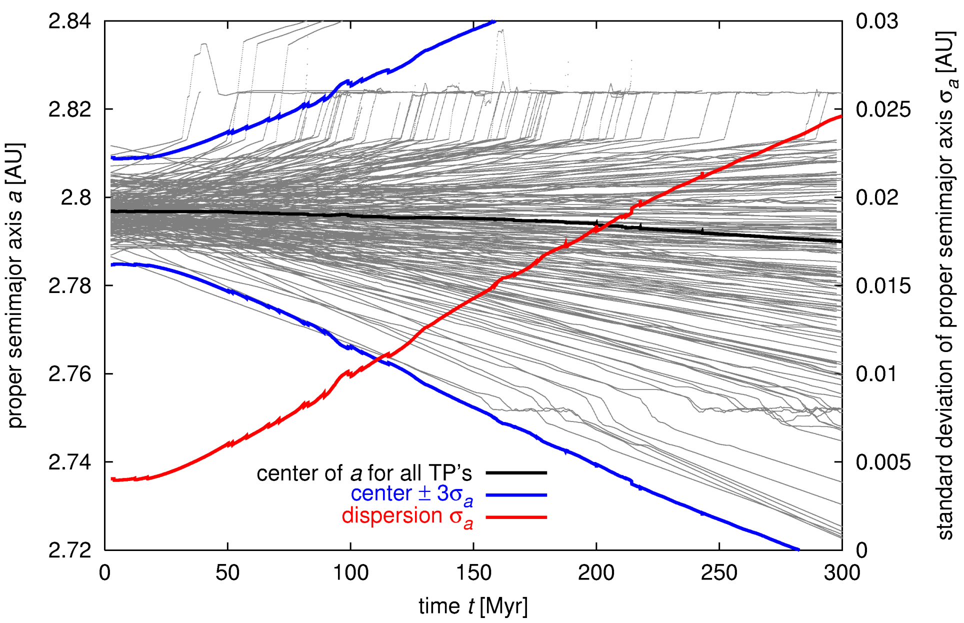
Dora:

Position of the Dora family is bracketed by the powerful J5/2 resonance and a complex of two resonances: J13/5 and 3J–1S–1 (see also page 5). We show the "proper" elements, computed as 5 Myr averages, for 210 integrated Dora (test) members over 300 Myr. Asteroids reaching the J5/2 resonance are quickly scattered on planets (the 4 bodies that crossed this resonance would have been scattered on inner planets if these were included in the simulation). Asteroids reaching the J13/5 and 3J–1S–1 zone are largely dispersed in the value of their proper e and are most likely unidentified as the Dora members.



Note: Symbols indicate the observed Dora members.

Below we show the temporal evolution of the proper a (left ordinate) for the our test asteroids, their mean value a_c computed for remaining asteroids and the standard deviation σ_a of their distribution (right ordinate).

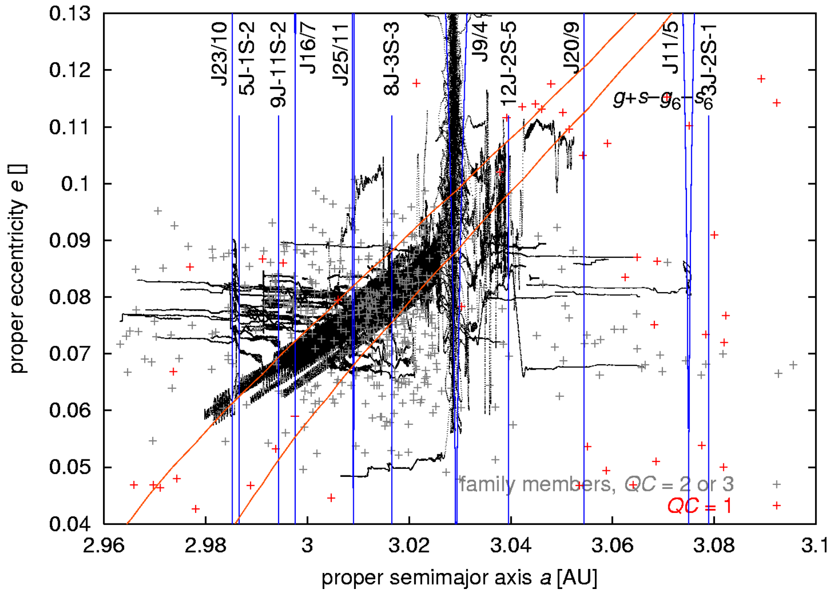


As time increases, the center of the family moves to smaller and smaller values as objects reaching the J5/2 resonance are eliminated. The mean dispersion increases in time (as a result of the Yarkovsky mobility in the family).

Eos:

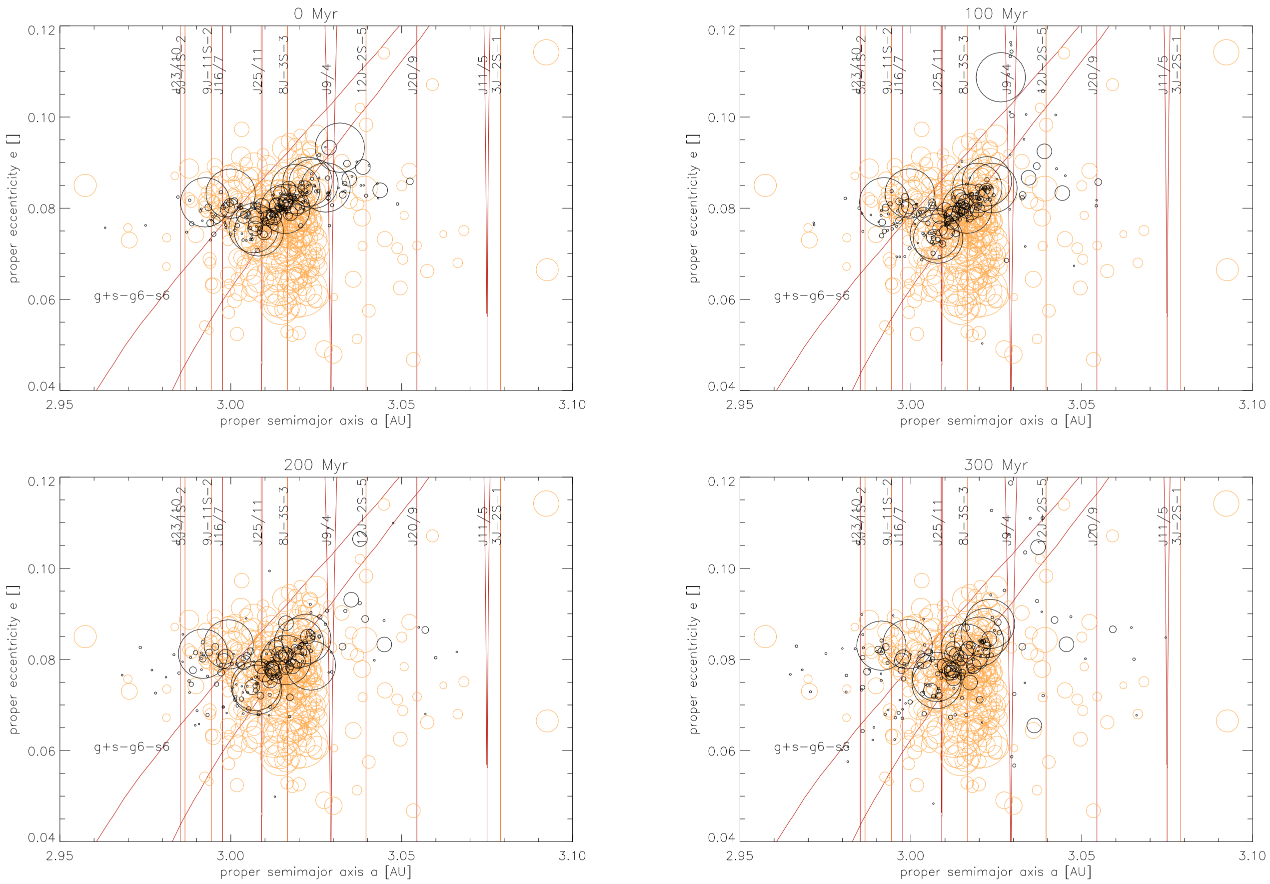
- Evolution tracks of the 210 Eos asteroids over 300 Myr; relevant mean–motion and secular resonances shown in blue and orange; symbols indicate real Eos members.

  Note: The z_1 resonance is a tiny structure whose position depends on all "proper" elements; in the following figures we have plotted its position for a particular value of the inclination. This explains why the evolution of these objects deviates from its center.



- 100 Myr – snapshots of our simulation with symbols indicating now the sizes of both integrated objects (black) and real Eos asteroids (orange).

  Note: Yarkovsky mobility scales with "1/size", i.e. assuming 3 times longer evolution (≈ 1 Gyr), approximately 3 times larger objects may evolve the same amount in proper a as our smallest objects, being also more dispersed in proper e and i.

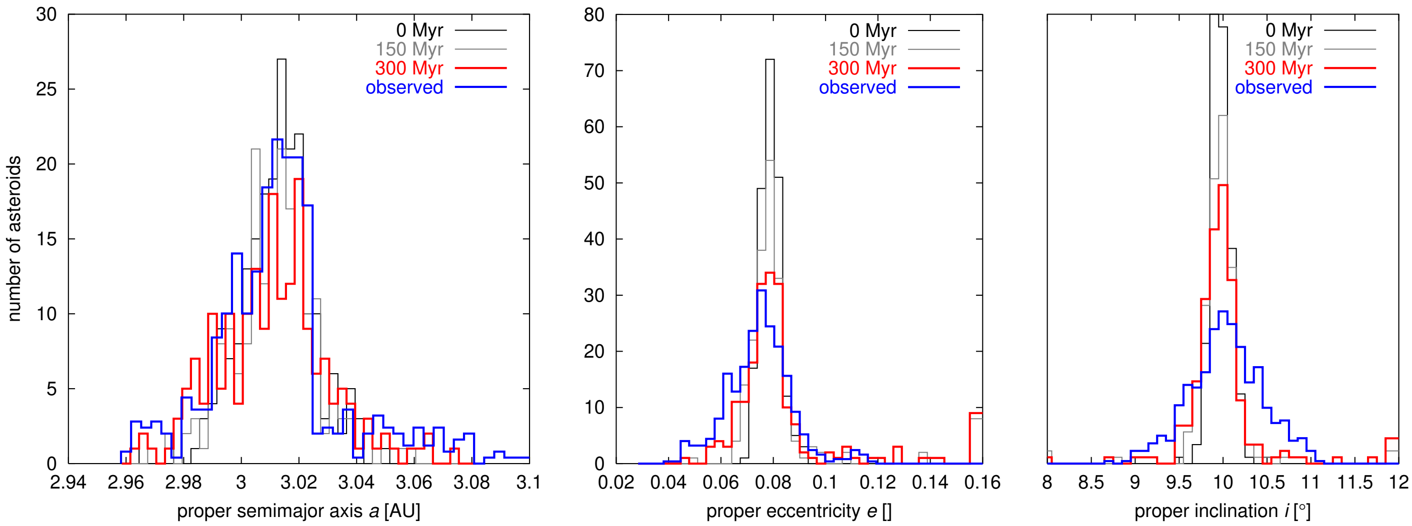


Eos — continued:

Eos long–term evolution is affected principally by two resonances: (i) J9/4 mean motion resonance, and (ii) $z_1 = g+s-g_6-s_6$ secular resonance. While the role of the first has been studied to some extent in the past, here we focus on the latter resonance. We suggest that evolution along the z_1 resonance might be diagnostic of semimajor axis mobility in the family.

On the left page 10 we plot results showing the 300 Myr simulation of 210 Eos orbits. We have computed "proper elements", as 5 Myr averages, and projected them onto the proper a vs. proper e plane. Note how the major resonances in this family affect the evolving orbits: (i) the J9/4 resonance causes rapid instability, with objects escaping to large e values, while (ii) the z_1 resonance attracts many of the evolving orbits and drives them to smaller eccentricity (and inclination) values. when objects drifting along the z_1 resonance encounter the J9/4 resonance, they are lost. This explains why there virtually no asteroids "sliding" along the z_1 resonance at larger eccentricity.

Below we show the temporal changes in the proper element distribution of the simulated Eos family, compared with the distribution of the observed Eos members (whose total number was recalibrated to 210).



Eos — testing the role of the z_1 resonance with orbits of 520 real members:

To test the possibility that the shape of the Eos family in proper element space has been affected by evolution of the orbits along the z_1 resonance (such as seen in the first figure on page 10), we need to determine which of its members are located in this resonance. To that end, we integrated the orbits of 520 observed Eos members for 30 Myr and analyzed the corresponding critical angle. We found 162 asteroids, i.e. **31 %** family members currently **residing in this resonance**.

Next, we analyzed the possible fine structures in the shape of the Eos family (like seeking a "jet" along the z_1 resonance). Note, however, that this procedure requires attention since the z_1 resonance has a fine 3D structure in proper element space. Rather than projecting the position of all Eos members onto one plane in the proper element space, we cut the family in tiny "slices" in the proper inclination and analyzed the structure of the Eos family separately on different layers in the inclination (see page 12). A slight excess of the "background" asteroids along the z_1 direction, "streaming" from the family at low inclinations, might support our hypothesis of the long–term semimajor axis mobility in this family. We propose that further family–identification procedures should take care of these fine processes (a similar conclusion were found for the Maria and Koronis families).

Eos — continued:

Eos members located in the 0.25° thick "slices" of the proper inclination.

- red bars: resonant proper elements of the 162 Eos members in the z_1 resonance;
- blue squares: asteroids at the edge of the z_1 resonance;
- black crosses: other members of the family according to A. Cellino data;
- gray dots: background asteroids (or not yet identified family members).