Asteroid Families

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CD07, Alicante
Current appearance of Families

130,000 objects, January 2007
Source: AstDys (A. Milani)
Asteroid Families

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Alberto Cellino – CD VII, Alicante, June 2007

- Physics of collisional disruption phenomena
- Asteroid Collisional Evolution
- Asteroid inventory and size distribution
- Asteroid Dynamical Evolution
- Asteroid interiors
- Meteorite showers
- Formation of Binary Systems
- Origin of near-Earth Asteroids
Asteroid Families: The Fundamental Problem for the purposes of Catastrophic Disruption Studies:

To be able to quantitatively understand how the observable properties of asteroid families have changed in time since their birth as a consequence of different evolutionary processes, in order to identify the information that current family data can provide about the physics of the original collisional events that produced these groupings.
Thesis (20th Century Families)

Antithesis (21st Century Families)

Synthesis ??

W.F. Hegel
### The Big Debate

<table>
<thead>
<tr>
<th>The Big Debate</th>
<th>XX Century</th>
<th>XXI Century</th>
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<tbody>
<tr>
<td>SFD at small sizes</td>
<td>Steep</td>
<td>Shallow</td>
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<td>Ejection velocities of the fragments</td>
<td>High</td>
<td>Low</td>
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<td>Main evolutionary mechanism</td>
<td>Collisions</td>
<td>Yarkovsky/YORP</td>
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<tr>
<td>Present family structures primarily due to:</td>
<td>Ejection velocity fields</td>
<td>Yarkovsky drift + nearby resonances</td>
</tr>
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XXth Century Results

Families' size distributions are steeper than the theoretical equilibrium slope for a collisionally relaxed population.

Background objects' size distributions are shallower than the equilibrium value.

(Cellino et al., 1991, MNRAS)
The role of geometry and of the finite volume of the target
Sometimes simple models fit nicely observational data!

(Tanga et al., 1999)
Recent confirmations from SPH/N-body simulations, but more families (~20) with a parent body larger than 100 km were found.
It could be possible in principle that the asteroid inventory at small sizes might be dominated by family members, depending on the time scales of family erosion. This is not confirmed by observational evidence, but the situation is not yet completely clear.
The size distribution used by Bottke et al., (2005).

\[ N \geq 1 \text{ km} \sim 1.2 \times 10^6 \]

To be compared with SDSS estimate:

\[ N \geq 1 \text{ km} \sim 7 \times 10^5 \]

(Ivezic et al., 2001, 2002)

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<th>( H )</th>
<th>( D )</th>
<th>( dN )</th>
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**Caveat: Large Errors in catalogues of Absolute Magnitudes**


Horizon Absolute Magnitudes vs. their Difference with MPC Absolute Magnitudes.
Absolute magnitude ($H_{\text{Obs}}$) (computed from V mags observed in a recent IRTF program) vs. $H_{\text{Obs}}$ minus the JPL Horizon element Catalog’s absolute magnitude ($H_{\text{Cat}}$) for all main-belt Intermediate Source Region asteroids observed through December 2004. The median difference is 0.24 mag and the mean difference is 0.22 mag. The linear correlation coefficient of the fit is 0.55.

Assuming that families dominate the inventory

SAM cumulative diameter frequency distribution. The lower curve indicates the distribution using the numbered asteroid data set for numbers <8604. The open squares are the entire SAM data set and the heavy curved line shows a least-squares third-order polynomial fit to the SAM data set for log D ≤ 2:0. The vertical dashed lines indicate the diameter completeness limits at the inner and outer edges of the main belt.

Tedesco et al., (2005). \( N \geq 1 \text{ km} \sim 1.7 \cdot 10^6 \)
Asteroid Families

Different models of the asteroid size distribution
Significant discrepancies (a factor between 2 and 3 at 1 km) exist between the results of ground-based surveys at visible wavelengths (SDSS, Subaru) and thermal IR observations from space. Waiting for PAN-Starrs!

Previous ISO results are preliminarily confirmed by a new Spitzer – VLT – CFHT survey (paper in preparation).
The final solution of this problem will be very important in many respects:

- Inventory and size distribution of the population
- Collisional evolution rate
- Role of families
- Physics of catastrophic disruptions
- Time-scales of non-collisional evolutionary mechanisms

On the other hand, the fact that SFD of freshly-formed families should be quite steep seems now more commonly accepted. Implications for meteorite showers.
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Size distribution of the very young Karin family

(Nesvorny and Bottke, 2004)

Ongoing polarimetric study at VLT to compare Karin members albedos with the albedos of surrounding Koronis members. Very important input for space weathering studies! Results of the analysis are imminent.

SFD Slope = -5.3!
Asteroid Families

Families as possible sources of near-Earth objects and meteorite showers.

Sooner (velocity field) or later (Yarkovsky) they go!

(From Gladman et al., 1997)
- Newly-born families are compact
- Very soon small family members start to “fly away”
- Escaping family members are easy targets of resonance traps

The Yarkovsky concept
The value of the Yarkovsky acceleration depends on many physical parameters:

- Obliquity angle
- Spin rate
- Object size (it vanishes for both large and very small sizes)
- Surface conductivity (thermal inertia)
- Heliocentric distance: \( \frac{da}{dt} \approx a^{-2} \)

Very nice example of a link between physical and dynamical properties (justifying the merging of IAU Commissions 15 and 20, by the way). The problem is that the effect is intrinsically quite complicated.
Computed mean drift rates in semi-major axis produced by the Yarkovsky effect in the inner belt for different possible values of thermal surface conductivity $K$ (W/m$^2$)

(a): 1 My

(b): collisional lifetime

(Bottke et al., 2006)
Numerical simulations of family evolutions due to the Yarkovsky effect. Trying to determine family ages.

Simulated evolution of the members of the Koronis family under the effect of the Yarkovsky effect. (Bottke et al., 2001, 2006)
The YORP effect
(Yarkovsky-O'Keefe-Radzievskii-Paddack)

Spin up of an asymmetrical asteroid. The asteroid is modeled as a sphere with two wedges attached to its equator. The asteroid is considered a blackbody, so it absorbs all sunlight falling on it and then reemits the energy in the infrared as thermal radiation. Because the kicks produced by photons leaving the wedges are in different directions, a net torque is produced that causes the asteroid to spin up.

(Bottke et al., 2006)
YORP depends on the object’s shape, size, thermal conductivity, heliocentric distance and obliquity angle.

An object must have some “windmill” asymmetry for YORP to work; energy reradiated from a symmetrical body (e.g., a sphere or an ellipsoid) produces no net YORP torque.

YORP can either spin up or spin down an object depending on its shape and rotation.

YORP torque produces also a change of obliquity angle. The obliquity angle tends to reach an asymptotic value. In turn, however, when the obliquity angle increases sufficiently, the rotation rate changes, and possibly tumbling rotation occurs before a new stable rotation state is reached again, and so on, leading to the possible occurrence of YORP cycles.
YORP-induced mean rate of change of the rotation rate $\dot{\omega}$ and obliquity as a function of the obliquity for asteroid (6489) Golevka (assumed to be on a circular orbit at 2.5 AU).

Eleven values of the surface thermal conductivity $\log K = -9, -8, \ldots , -1, 0, 1$ are shown.

The rotation effect shows a small dependence on $K$, whereas the obliquity effect has a significant dependence on $K$ (and rotation period of 6 h).

Asymptotic obliquity angles: 0, 180, 90

YORP is very important for its effect on the Yarkovsky evolution, since it affects the rotation state
Koronis Family

Distribution of spin axis directions from extensive photometric observations

Bimodality possibly produced by YORP + spin-orbit resonance evolution

Waiting for new examples (Gaia, PAN-STARRS)

(Sliwan, 2002 and Sliwan and Binzel, 2003)
Problems

- Up to which size Yarkovsky+YORP (+spin-orbit resonances) produce recognizable effects over times comparable to family ages?
- Can the initial family structures and velocity fields be estimated from the properties of the largest members?
- Explanations of $D$ vs. Proper elements relations (specially $e$ and $i$)
- Need of putting together the effects of mechanisms having different, and size-dependent time scales (resonance crossing, resonance-driven dynamical evolution, spin axis collisional realignment).
- Role of non-catastrophic collisions
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2007 data
The dispersions of eccentricities and inclinations often appear to be inversely proportional to asteroid size (in agreement with the existence of a size-velocity relation).

Can this be explained by a scenario of pure Yarkovsky + resonances evolution?
The random walk of Main Belt asteroids: orbital mobility by non-destructive collisions

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Accepted ... Received ...; in original form ...

\textbf{ABSTRACT}

Non-destructive collisions among Main Belt asteroids have effects on their orbits due to the transmission of linear momentum. The efficiency of this mechanism depends on several parameters which are currently poorly known. The most critical aspects are: (1) the inventory and size distribution of small Main Belt asteroids, with sizes well below a few kilometers; (2) the energy threshold for collisional fragmentation and fragment dispersion; (3) the efficiency of linear momentum transfer. In spite of these difficulties, a general statistical model of the dynamical effects of non-destructive collisions can be developed, and is presented here. Based on this model, the consequences of different assumptions concerning the asteroid size distribution and collision physics are computed and discussed. Quantitative evaluations of the collisionally-induced orbital mobility in different possible scenarios are presented.

\textbf{Key words:} minor planets, asteroids, meteoroids.
In the full complexity of natural processes, the present structures of asteroid families must be determined by the interplay of different mechanisms:

**The initial Velocity Field:** the initial distribution of the proper elements is due to the distribution of the ejection velocities \( V_\infty \)

**The Yarkovsky effect:** the original distribution of the proper elements is progressively modified by post-formation dynamical evolution:

**The subsequent collisional evolution of the family members:** family erosion due to both low- and high-energy collisions
The dispersions are not correlated: so they sum together quadratically:

$$\Delta a_Y^2 + \Delta a_0^2 = \Delta a^2$$
The diagram shows the relationship between $D$ (km) and $a$ (AU) with an expansion time of $T_Y = 4000$ Myr. The graph illustrates the distribution of points and the following curves:

- Red dashed line: $T_Y = 4000$ Myr
- Green dashed line: Another curve for comparison

The diagram is labeled with the title "Themis" and includes a title box "Expansion Time: $T_Y = 4000$ Myr."
The initial ejection velocity values of family members are not uniquely constrained.

Pre-Yarkovsky models accepted values exceeding 100 m/sec

Hydrocode models of break-up phenomena give much smaller values (less than 10 m/sec)

The first Yarkovsky-based investigations assumed negligible initial ejection velocities

More recent Yarkovsky analyses (reconstruction of the Eos family) deal with initial velocities of some 10 m/sec.

For Karin, velocities of 20 m/s have been inferred, higher values cannot be ruled out, and relatively large fragments of 3-km in size have speeds around 10 m/s (Nesvorny et al., 2006).
### TABLE 1

**OSCULATING ORBITAL ELEMENTS**

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>a/a_0 (AU)</th>
<th>e/e_0</th>
<th>i/ι (deg)</th>
<th>ω/ω (deg)</th>
<th>Ω/Ω (deg)</th>
</tr>
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<tbody>
<tr>
<td><strong>Datura Cluster</strong></td>
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<tr>
<td>1270 Datura</td>
<td>2.23555349(11)</td>
<td>0.2075042(13)</td>
<td>5.9876230(86)</td>
<td>258.68066(14)</td>
<td>97.90401(14)</td>
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<td>60151 1999 UZ6</td>
<td>2.23470878(21)</td>
<td>0.20750512(36)</td>
<td>5.993636(21)</td>
<td>260.77803(27)</td>
<td>96.80238(25)</td>
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<tr>
<td>89309 2001 VN36</td>
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<td>0.20731883(50)</td>
<td>6.020404(19)</td>
<td>266.77862(23)</td>
<td>92.99934(19)</td>
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<td>90265 2003 CL5</td>
<td>2.23468648(16)</td>
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<td>5.982925(30)</td>
<td>262.00113(32)</td>
<td>95.70379(30)</td>
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<td>0.20838304(12)</td>
<td>5.9903231(29)</td>
<td>260.39857(88)</td>
<td>96.89528(22)</td>
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<td>2003 SQ168</td>
<td>2.23553274(71)</td>
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<td>5.98895(14)</td>
<td>259.229(20)</td>
<td>97.4898(30)</td>
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<td>2003 UD112</td>
<td>2.2342(18)</td>
<td>0.20614(55)</td>
<td>5.09090(83)</td>
<td>263.14(31)</td>
<td>95.47467(67)</td>
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<td><strong>Emilkowski Cluster</strong></td>
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<td>17.73545(36)</td>
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<td>17.75656(22)</td>
<td>42.47166(40)</td>
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<td>2005 WU178</td>
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<td>17.75416(22)</td>
<td>42.8675(19)</td>
<td>42.34248(20)</td>
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<td><strong>1992 YC2 Cluster</strong></td>
<td></td>
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<tr>
<td>16598 1992 YC2</td>
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<td>0.22081556(12)</td>
<td>1.628026(16)</td>
<td>105.13893(53)</td>
<td>287.06871(53)</td>
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<td>2004 XL40</td>
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<td>5.98458(80)</td>
<td>4.55563(42)</td>
<td>70.1286(42)</td>
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</table>

**Notes.** — Keplerian orbital elements are given for epoch MJD 2,455,700.5. The values of mean anomaly, not listed here, show no clustering. The 1σ uncertainties of the orbital elements in the last two decimal digits are shown in parentheses. They are roughly inversely proportional to the length of the observational arc. Asteroid 1270 Datura, first discovered in 1930, has the most accurately determined orbital elements. Single-opposition asteroids 2003 SQ168 and 2003 UD112 in the Datura cluster have the largest uncertainties. For 2003 UD112, the orbit uncertainties in a, e, and i are comparable to the orbital spread of the Datura cluster.
Families as likely producers of many binary systems

Modern models of catastrophic disruption events predict that these phenomena should be expected to produce many binary systems among the fragments (Michel et al., several papers). Waiting for Gaia!
Next developments

- New, updated Families needed with particular attention to overlapping and distance level for membership assessment.
- More Spectroscopic data, to be used for membership
- Need of better estimates of Yarkovsky parameters, and role of YORP and spin-orbit resonances.
- Interpretation of Proper elements vs. D plots
- New refined numerical simulations (hydrocodes).
- New Photometric data
- Space missions (Gaia)
The choice of the membership criterium has big implications for the understanding of family properties, and for the assessment of the inventory of the background, non-family population.