A six-part collisional model of the main asteroid belt

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Milani & Kneževic (2003)
Masiero et al. (2011)
Motivation

- New data (albedos and diameters for 129,750 asteroids) from the WISE satellite (Masiero et al. 2011)
- Test if a single scaling law can be used for the whole main belt (Benz & Asphaug 1999)
- To decide if asteroids are rather monolithic or rubble-piles? (simulations from Durda et al. 2007, Benavidez et al. 2012)
- We focus on the last ~3.85 Gyr only (i.e. post-LHB)!
Observational data from WISE

- 6 parts of the MB: inner, middle, `pristine`, outer, Cybele, high-inclination
- reconstruction of the SFDs for 535,630 asteroids (a Monte-Carlo method)

we also computed intrinsic probabilities $p_i$ and impact velocities $v_{imp}$ (Bottke & Greenberg 1993)

observational bias
Observed asteroid families

- we use the list of 82 families from Brož et al. (2013), with a few additions (Walsh et al. 2013)
- essentially compatible with lists of Masiero et al. (2013), Nesvorný (2012)
- we need also physical parameters ($D_{PB}$, $M_{LR}/M_{PB}$ ratio) to distinguish catastrophic disruptions (methods of Durda et al. 2007, Tanga et al. 1999)

Table 1. A list of asteroid families and their physical parameters.

| Designation | $a_{cut}$ | N | $p_V$ | Tax. | $D_{PB}$ km | $D_{Durch}$ km | LR/PB | $v_{esc}$ m/s | $q_1$ | $q_2$ | Age Gyr | Notes, references |
|-------------|-----------|---|-------|------|-------------|---------------|-------|--------------|------|------|---------|-----------------|
| 3 Juno | 50 | 449 | 0.250 | S | 233 | ? | 0.999 | 139 | -4.9 | -3.2 | <0.7 | cratering, Nesvorný et al. (2005) |
| 4 Vesta | 60 | 11 169 | 0.351 | V | 259 | 425 | 0.995 | 314 | -4.5 | -2.9 | 1.0 ± 0.25 |
| 8 Flora | 60 | 3284 | 0.304 | W | 150 | 160 | 0.81–0.68 | 88 | -3.4 | -2.9 | 1.0 ± 0.5 |
| 10 Hygiea | 70 | 3122 | 0.055 | C.B | 410 | 442 | 0.976–0.78 | 243 | -4.2 | -3.2 | 2.0 ± 1.0 |
| 15 Eunomia | 50 | 2867 | 0.187 | S | 292 | 292 | 0.958–0.66 | 153 | -5.6 | -2.3 | 2.5 ± 0.5 |
| 20 Massalia | 40 | 2980 | 0.215 | S | 146 | 144 | 0.995 | 86 | -5.0 | -3.0 | 0.3 ± 0.1 |
| 24 Themis | 70 | 3581 | 0.066 | C | 158 | 27.4–30 | 0.43–0.09 | 158 | -2.7 | -2.4 | 2.5 ± 1.0 |
| 44 Nysa (Polana) | 60 | 9957 | 0.278 | S | 81c | ? | 0.65 | 48 | -6.9 | -2.6(0.5) | <1.5 |
| 46 Hestia | 65 | 95 | 0.053 | S | 124 | 153 | 0.992–0.53 | 74 | -3.3 | -2.0 | <0.2 |
| 87 Sylvia | 110 | 71 | 0.045 | C/X | 261 | 272 | 0.994–0.88 | 154 | -5.2 | -2.4 | 1.0–3.8 |
| 128 Nemesis | 60 | 654 | 0.052 | C | 189 | 197 | 0.987–0.87 | 112 | -3.4 | -3.3 | 0.2 ± 0.1 |
| 137 Meliboea | 95 | 199 | 0.054 | C | 174c | 240–290 | 0.59–0.20 | 102 | -1.9 | -1.8 | <3.0 |
| 142 Polana (Nysa) | 60 | 3443 | 0.055 | W | 75 | ? | 0.42 | 45 | -7.0 | -3.6 | <1.5 |

cont. below ↓
The scaling law and fragment SFDs

- scaling law expressed as:
  \[ Q_D^* = \frac{1}{q_{\text{factor}}} \left( Q_0 r^a + B \rho r^b \right) \]

- we need also parametric relations describing outcomes of disruptions:
  largest fragment mass \( M_{\text{LF}} \)
  and SFD slope \( q \) vs \( Q/Q_D^* \)
Model, parameters, $\chi^2$ metric

- Boulder code (Morbidelli et al. 2009), particle-in-a-box + SPH
- 36 free parameters: initial SFD slopes, ranges, normalization
- fit for SFD’s @ $t_{\text{end}} = 4$ Gyr and the # of families:
  \( \text{syn, obs} \) ... either $N(>D)$ or $N_{\text{fam}}$
- weighting $w_{\text{fam}} = 10$

\[
\chi^2 = \sum_{i=1}^{N=96+6} \frac{(\text{syn}_i - \text{obs}_i)^2}{\sigma_i^2}
\]
a wide range of

**Initial conditions (for simplex)**

- 729 different SFDs * 300 iterations = 218,700 simulations
- convergence to a local minimum is difficult ← stochasticity!

disruptions of large PB depend on the random seed
Results for monoliths

- problems with some SFDs! (for $D = 1$ to $10$ km)
- the best fit $\chi^2 = 613$, or 512 after a detailed analysis

families are OK
Results for rubble-piles
and the same set of iniconds...

- the ‘best’ fit $\chi^2 = 1602$ only, i.e. much worse than for monoliths!
- the main belt is *not* composed of (pure) rubble-piles?
Possible

Improvements of the model?

- use a longer SFD `tail' \((D_{\text{min}} = 0.01 \text{ km})\)
- account for the Yarkovsky effect dynamical decay \(N(t+\Delta t) = N(t) \exp \left( \frac{\Delta t}{\tau_{YE}} \right)\)
- optimize sequentially the 6 parts of the MB
- none of these works!

\[ \tau_{YE}(D) \]
\[ \omega(D) \approx 1/D \]
\[ \omega(D) \approx D^{-1.5} \]

\[ N(t+\Delta t) = N(t) \exp \left( \frac{\Delta t}{\tau_{YE}} \right) \]

a test for a single MB: we can exclude low \( K \) & \( \omega \)
Conclusions and future work

- indeed different scaling laws for different parts of the MB?
- improve the scaling of $D_{PB} = 100$ km disruptions?
- the evolution is too stochastic ($N \sim 10^0$) → prescribe large disruptions (i.e. a deterministic model)?
- improve the YE model (using N-body simulations)?
- some of $v_{imp} > 5$ km/s → use a velocity-dependent scaling law? (e.g. Leinhardt & Stewart 2012)
- family lists are strongly biased? (Walsh et al. 2013)
- etc.?