Planetesimals embedded in protoplanetary discs versus mean-motion resonances

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Introduction & Motivation

Aims. We hereby present preliminary results of our study focused on the dynamics and collisional behavior of planetesimals embedded in a protoplanetary disc which are delivered into mean-motion resonances with a giant Jupiter-like planet via the aerodynamic drag. As pointed out by Marzari & Weidenschilling (2002), resonant perturbations can overcome the damping effects of the drag and produce eccentric orbits in an otherwise cold belt of planetesimals, leading to an increased collisional fragmentation. Our aim is to numerically investigate such a system, addressing the following two problems.

Early capture in the resonances. In a recent work of Chrenko et al. (2015), we realized that stable islands of the 2:1 mean-motion resonance with Jupiter partially retain their stability during a jump of Jupiter (induced by late planetary close encounters). It is thus possible that part of the observed long-lived asteroids consists of primordial objects. An open question is whether a primordial population can even form inside the MMRs.

Relation to the sizes of primordial asteroids. It remains unclear whether the newborn asteroids were indeed big (Morbidelli et al. 2009) or small (Levison et al. 2015). We aim to investigate how does the presence of eccentric orbits produced by the aforementioned resonant excitation affects the collisional cascade and the primordial size-frequency distribution.

Method

We simulate orbital evolution of minor bodies embedded in a gaseous disc using a modified version of FARGO, a 2D hydrodynamic code described in Masset (2000).

Features of the current version of our code.

► N-body part of the code treats both massive bodies (planets, embryos, etc.) and a population of massless test particles (planetesimals in our case). We replaced the original Runge-Kutta integrator so that the equations of motion are now solved using the Bulirsch-Stoer integrator (Press et al. 1992) which subdivides the time step until the desired precision is reached ($\epsilon = 10^{-7}$).

► Test particles are subject to the gravity of the Sun and all massive perturbers and also to the drag of the surrounding nebular gas. They do not feel any other acceleration (such as the self-gravity, the gas disc gravity, etc.). Particles are allowed to evolve in **3 dimensions**, assuming an exponential vertical profile of the surrounding disc.

► The drag treatment is **local**, the hydrodynamic quantities $(\Sigma, v_\mathrm{r}, v_\theta)$ are interpolated from nine grid cell centers (or interfaces) in the neighborhood of each test particle. This approach is the same as in Morbidelli & Nesvorný (2012). The drag coefficient is then computed similarly to Adachi (1976).

Features to be implemented.

► Direct self-consistent treatment of collisions is yet to be implemented as well as mutual gravitational interactions of (former) test particles.

Hydro & N-body dynamics

Nebular gas. We simulate a portion of gaseous disc extending from 1.8 to 6 AU, with 200 x 343 resolution of the polar staggered grid. The planet-disc interaction is smoothed using the thickness smoothing parameter 0.6, the aspect ratio is *H*/*r* = 0.056 and the disc is non-flaring. The gas viscosity is parametrized using the Shakura-Sunyaev alpha, $\alpha = 6 \times 10^{-3}$. The standard MMSN model is used for the initial gas surface density (except Model 3, see below):

$$\Sigma = 1700 \left(\frac{r}{\mathrm{AU}}\right)^{-\frac{3}{2}} \mathrm{g\,cm^{-2}}$$

Planetesimals (as test particles). The initial belt of planetesimals is assumed to be relaxed by the gas drag, having $e < 0.002$ and $\sin I < 0.002$. In most of the simulations, we place several hundred test particles directly at the outer separatrices of major Jovian MMRs. We separately study planetesimals with various physical radii, here we present three cases with *R* = 0.5, 10, and 100 km.

Jupiter. In the following models, Jupiter is assumed to be fully formed and orbits at 5.2 AU. No material is accreting on the planet.

► Model 1 — Jupiter's orbit is circular.

► Model 2 — Jupiter's orbit is moderately eccentric, with *e* = 0.02.

► Model 3 — Jupiter's eccentricity is the same as in Model 2 but additionally, we assume that the initial gas surface density is half the MMSN value.

See **Figure 1** and **Figure 2** for the results.

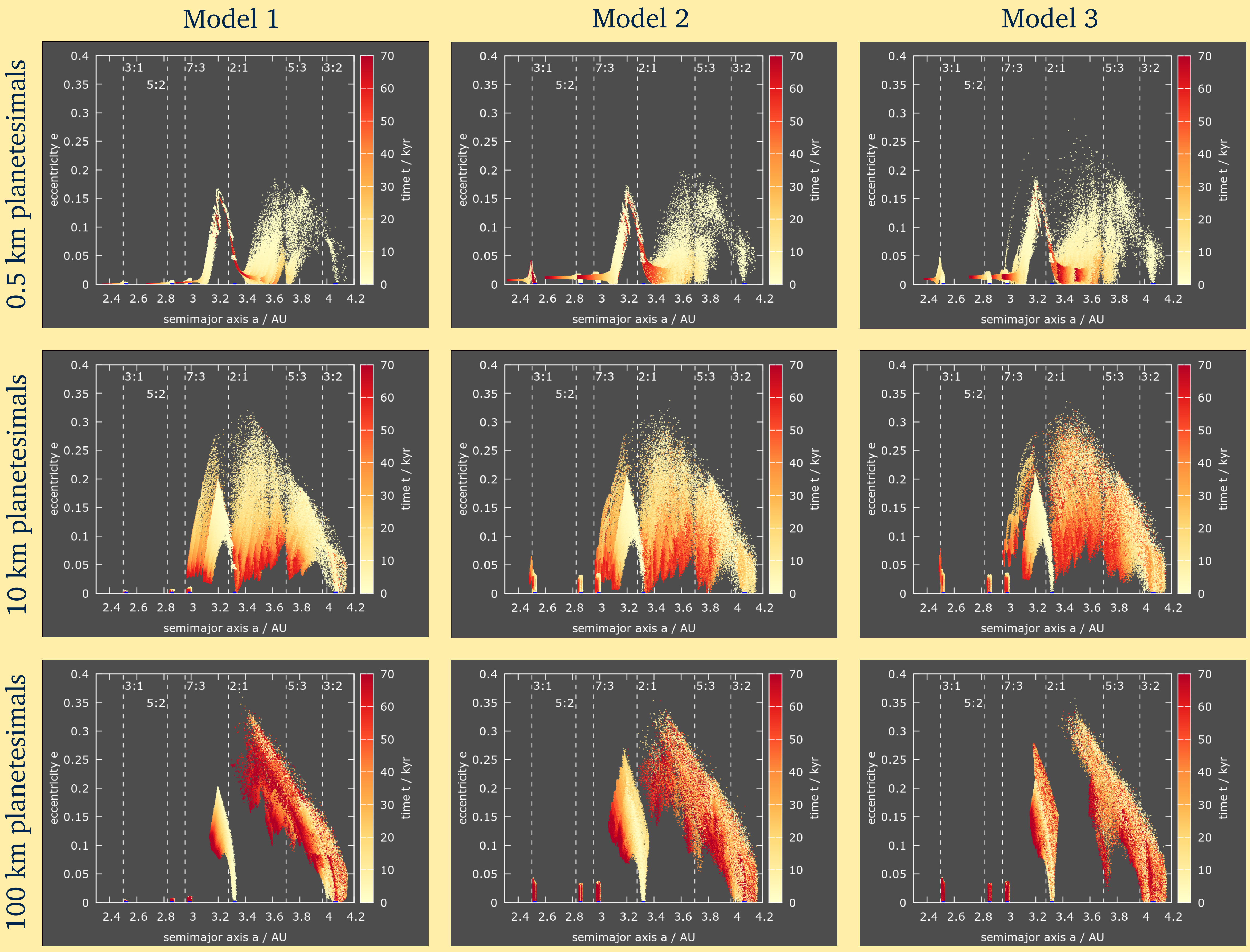
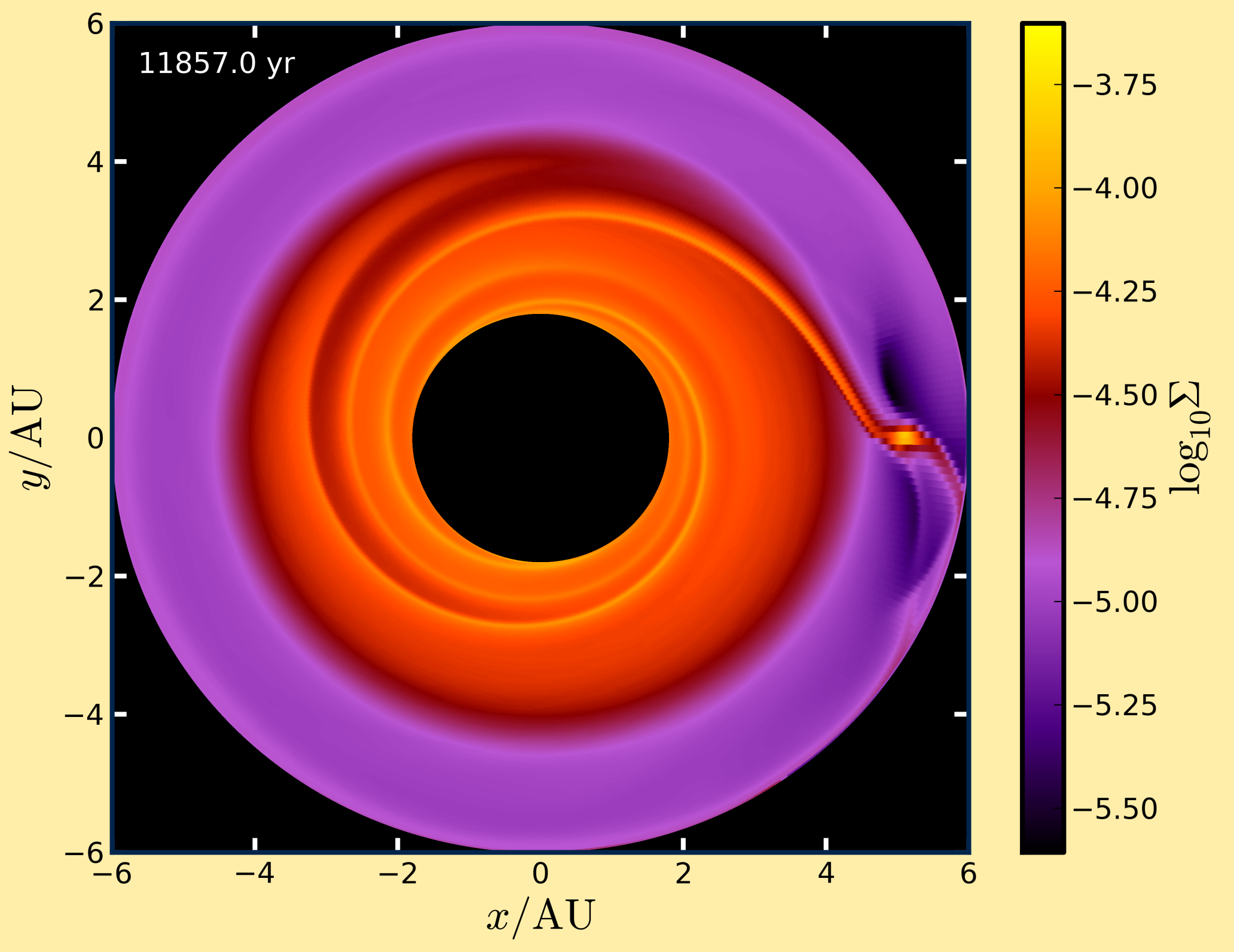
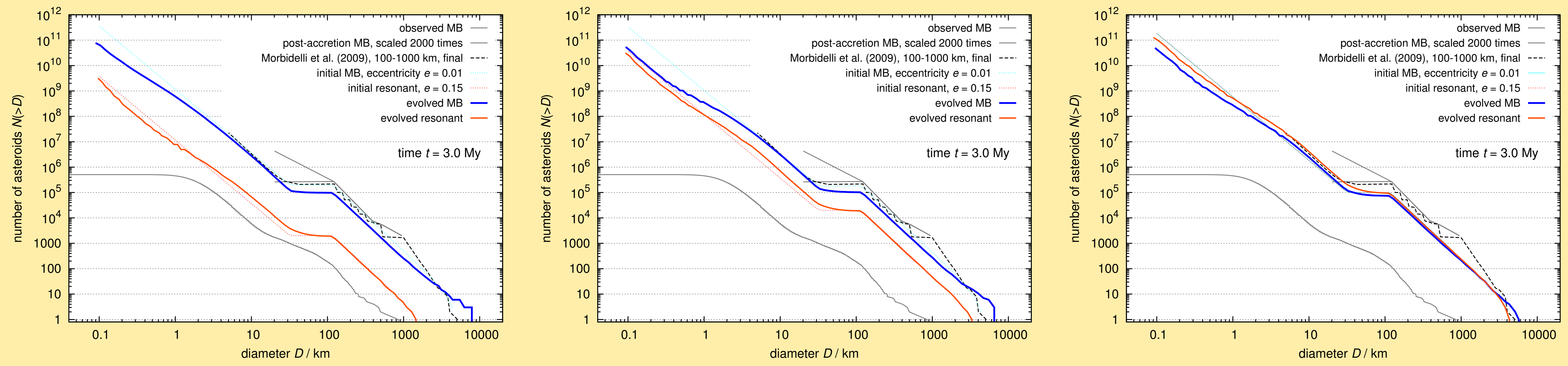


Figure 1 (top 9 panels): The evolution of test particles in the osculating (*a*, *e*) space. Each column corresponds to a different model, while each row represents a simulation with planetesimals of different physical radius. The color coding corresponds to the simulation time when the depicted elements were recorded. The overall timescale displayed here is 70 kyr. The time sampling of the osculating elements is 60 yr. Five hundred test particles are initially set near the 3:1, 5:2, 7:3, 2:1 and 3:2 resonances, having near-zero eccentricity (the location of initial orbits is marked by blue points).

Figure 2 (right): An example of the gas surface density profile in one of the Model 2 simulations. The displayed quantity is the common logarithm of the surface density expressed in the unit system with the gravitational constant and the mass of the primary being both unity. The figure was taken after approximately 12 kyr of the simulation. Jupiter is located at (5.2,0) AU.

Figure 3 (bottom 3 panels): Three realizations of our collisional model with different hot/cold ratios 0.01, 0.1 and 0.5 (cold planetesimals are assumed to orbit with *e* = 0.01, while hot planetesimals have *e* = 0.15). The state of cold and hot population after 3 Myr of collisions is depicted by solid blue and orange line, respectively.





Collisions

Here we estimate whether the accretion or fragmentation prevails in an excited planetesimal belt using the Boulder code (Morbidelli et al. 2009). To set up our initial synthetic population, we adopt a final SFD that was derived in Morbidelli et al. (2009) from an accretion model of 100 to 1000 km main-belt planetesimals. As they assumed that Jupiter was not yet formed, we 'continue' their simulation, spanning another 3 Myr, but our model differs in the following manner:

► The synthetic population is split into a rather cold belt (e ~ 0.01) and a hot part created by the resonant excitation (e ~ 0.15, as we derive from Figure 1). The **hot/cold ratio** is a free parameter which can mimic the orbital distribution resulting from our dynamic simulations.

► We do *not* incorporate the effects of viscous stirring, dynamical friction, isolated bodies, collisional damping and turbulent stirring.

► We note that only collisional fragmentation, reaccumulation and gravitational focusing are accounted for.

► We vary the hot/cold ratio to check if the presence of the excited population can strongly affect the final SFD.

See **Figure 3** for the results.

Results

Dynamics, see Figure 1.

A transition from Model 1 to Model 3: Generally, the eccentricity kick gets stronger, perturbations by higher-order resonances start to occur.

Small planetesimals (*R* = 0.5 km): The maximum eccentricity kick goes from 0.15 up to 0.2. The eccentricity damping is strong, thus the orbits are circularized fast (relatively to the simulation time span) and the particles continue to spiral inwards until they cross another resonance and so on.

Medium-sized planetesimals (*R* = 10 km): The eccentricity excitation reaches 0.3. There is a much larger spread of planetesimals over the phase space than in the previous case. Several planetesimals that were first excited by the 3:2 resonance reach the 2:1 resonance even before their eccentricity is fully damped, thus maintaining a non-circular orbit for a longer period of time.

Large planetesimals (*R* = 100 km): these bodies are rather decoupled from the gas, thus the resonant excitation lasts longer. In Model 3, there is a clump of particles that reside in the 2:1 resonance for the whole simulation span.

Collisions, see Figure 3.

For 0.01 and 0.1 hot/cold ratios, the evolved SFD of the cold planetesimal belt is:

► the same as the initial SFD for *D* < 20 km, with a wavy tail produced by a fragmentation cascade,

► 'depleted' (about half an order of magnitude at most) in the range *D* = 20 to 2000 km, while the slope does not evolve. This depletion is caused by the gradual accumulation of material leading to the formation of larger objects.

For 0.5 hot/cold ratio, the SFDs do not evolve as much as in the previous cases (fragmentation and accumulation are rather balanced). The accretion of objects larger than those that were initially present is halted.

Future work: simulation with the gas dispersal; implementation of neglected effects into the collisional model; self-consistent treatment of dynamics and collisions.

References & Acknowledgments

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