The Formation of Giant Planets and the Collisional Evolution of Planetesimals: Lessons Learned from the Solar System

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The early Solar System and its chronology.

The first phase in the lifetime of the Solar System was that of the Solar Nebula (see Fig. 1 and Coradini et al. 2011): during this phase, the Solar System was constituted by a circumsolar disk of gas and dust particles where planetary embryos and the giant planets were forming. The chronology of the early Solar System obtained through radiometric ages of meteorites (see Fig. 2) indicates that the first solids to form in the Solar Nebula, about 4568.2 Ma ago (Bouvier & Wadhwa 2010), were the Ca-Al-rich inclusions (CAIs). Differentiated bodies generally appeared in the next few million years after CAIs (see Scott 2007 and references therein). Basing on meteoritic data and theoretical results, Jupiter and the other giant planets should have appeared about 3-5 Ma after CAIs (Bottke et al. 2005, Scott 2006).

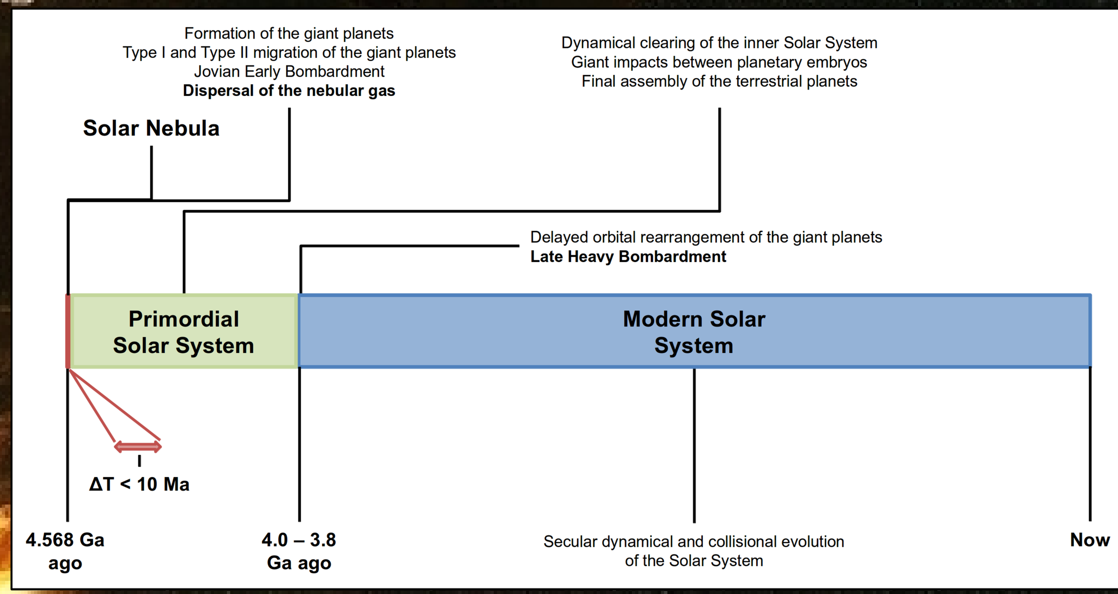

Figure 1: timeline of the Solar System from the condensation of the first solids, the Ca-Al-rich inclusions, to present. The events associated to the transitions between different phases are in bold fonts. Figure adapted from Coradini et al. (2011).

The Jovian Early Bombardment.

The formation of Jupiter, plausibly the first giant planet to appear in the Solar Nebula, triggered the first bombardment (i.e. a sudden spike in the flux of impactors) in the history of the Solar System (Safronov 1972; Weidenschilling 1975; Weidenschilling et al. 2001; Turrini et al. 2011, 2012).

This Jovian Early Bombardment (Turrini et al. 2011, 2012), was caused by two populations of impactors:

- Icy planetesimals in the outer Solar System scattered by Jupiter or affected by the orbital resonances it created (Safronov 1972; Weidenschilling 1975; Weidenschilling et al. 2001; Turrini et al. 2011);
- Rocky planetesimals ejected from the asteroid belt due of the effects of the Jovian orbital resonances (Turrini et al. 2011,2012).

The second population is the dominant one in the inner Solar System, being orders of magnitude larger than the first one (see Fig. 3).

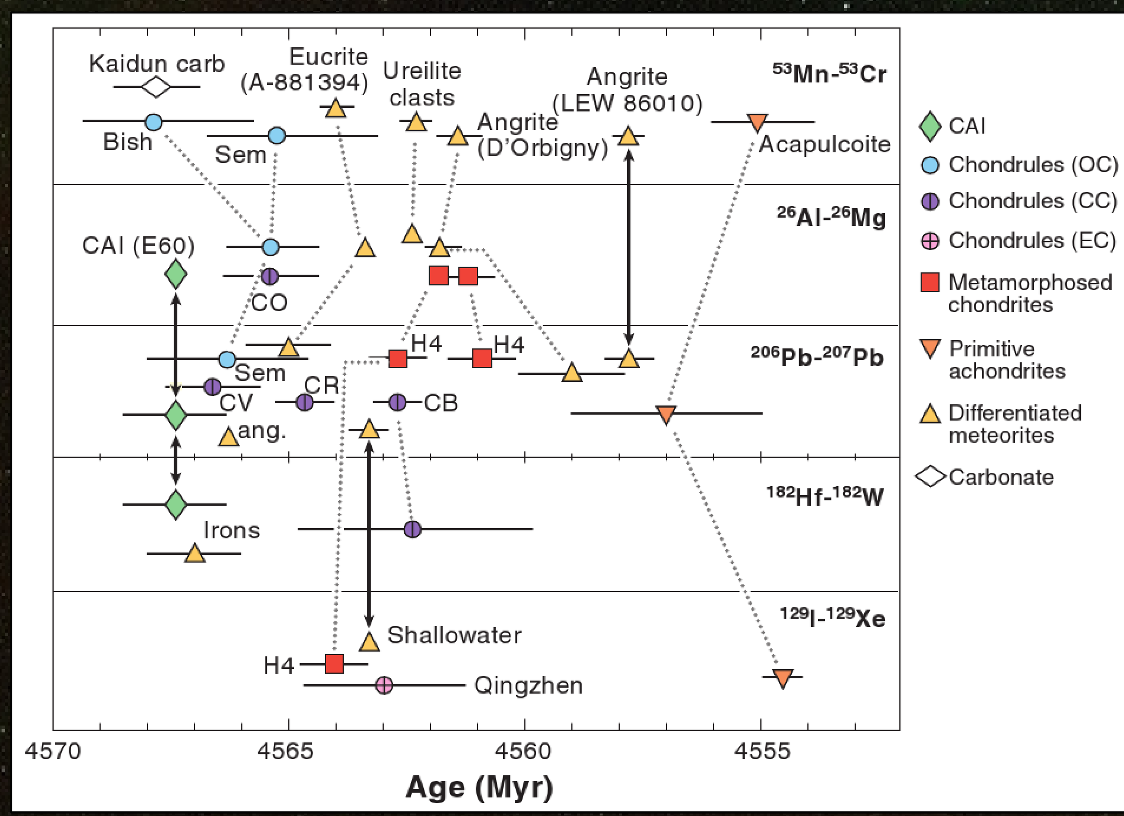

Figure 2: chronology of the formation and evolution of planetesimals inferred from the radiometric ages of meteorites. Figure from Scott (2007).

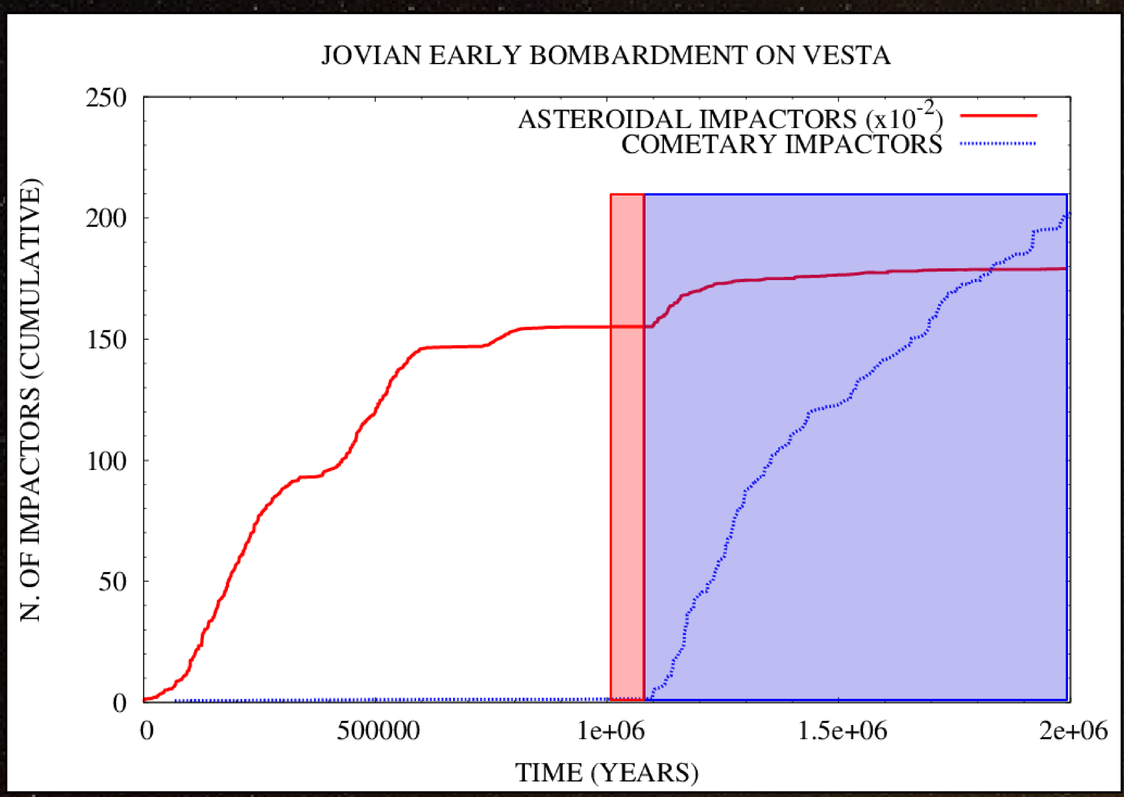

Figure 3: Comparison of the fluxes of cometary and asteroidal impactors during the Jovian Early Bombardment using Vesta as case study. The red area marks the temporal interval over which Jupiter is accreting, the blue one marks the Jovian Early Bombardment. The flux of asteroidal impactors has been divided by a factor 100. Figure adapted from Turrini et al. (2011).

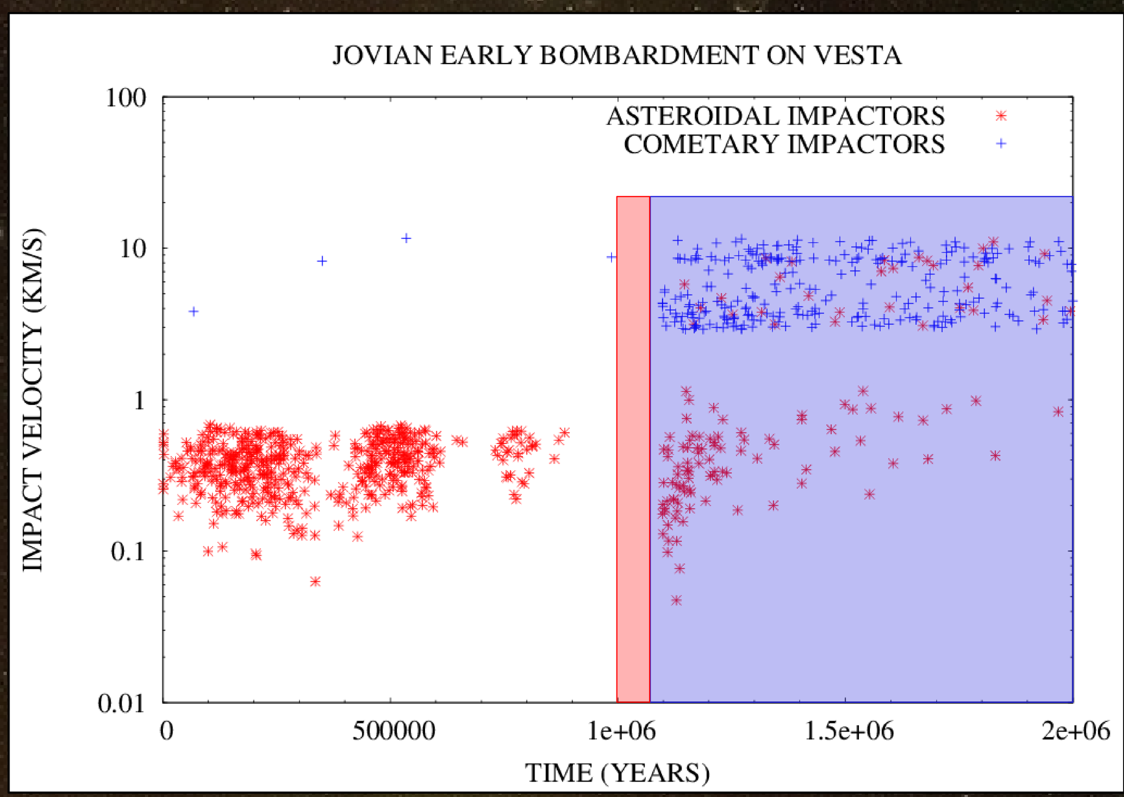

Figure 4: Evolution of the impact velocities in the asteroid belt during the Jovian Early Bombardment using Vesta as case study. The impact velocity of a growing fraction of the asteroidal impactors becomes larger than 1 km/s and impacts become erosive. Figure adapted from Turrini et al. (2011). See Fig. 3 for the meaning of the red and blue areas.

Intensity and duration of the Jovian Early Bombardment.

The Jovian Early Bombardment is relatively short, lasting about 1 Ma (Weidenschilling 1975; Turrini et al. 2011, 2012) with the bulk of the impacts concentrated in the first 3-5·10^5 years (Turrini et al. 2011, 2012).

During the Jovian Early Bombardment, the number of cometary impactors crossing the asteroid belt can significantly increase but the range of impact velocities (4-12 km/s) does not change (see Fig. 4). In the case of asteroidal impactors, both the numbers of projectiles and their impact velocities increase (see Fig. 4). While a large number of impact events with asteroidal projectiles still results in net accretion (see Fig. 4, impact speeds lower than 1 km/s), a growing fraction of asteroidal impactors achieves impact speed between 2-10 km/s (see Fig. 4) and causes net erosion.

Even if it is extremely short, the Jovian Early Bombardment is very intense due to the large, pre-depletion population of planetesimals in the asteroid belt (Weidenschilling 1977; see also Coradini et al. 2011 for a discussion of the Jovian Early Bombardment and the depletion process of the asteroid belt). In the most likely case (see Fig. 5, size-frequency distribution from Weidenschilling 2011) the bulk of the impactors is constituted by km-sized planetesimals (Turrini, submitted).

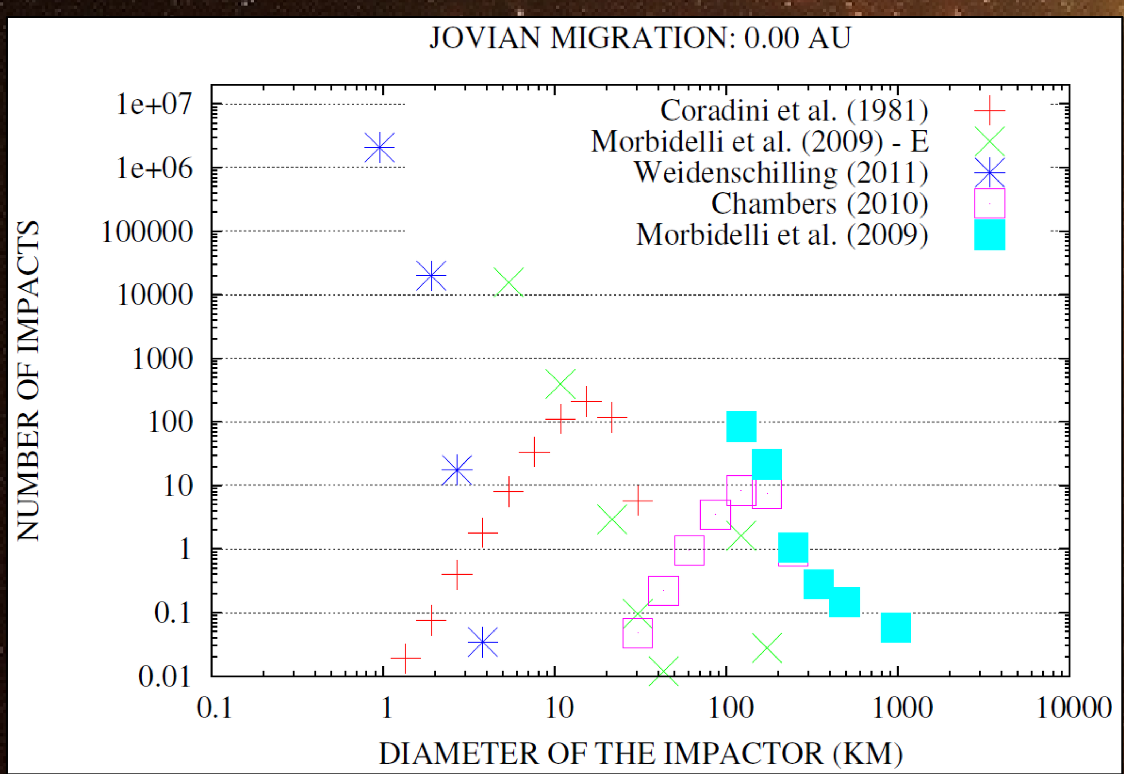

Figure 5: Size-frequency distributions of impactors during the Jovian Early Bombardment using Vesta as case study. The size-frequency distributions refer to planetesimals formed in quiescent disks (Coradini et al. 1981), turbulent disks (Chambers 2010; Morbidelli et al. 2009) and collisionally evolved planetesimals (Weidenschilling 2011; Morbidelli et al. (2009) – E). Only impacts occurring at velocities larger than 1 km/s are considered (Fig. 3 shows the case of Coradini et al. 1981 including also slower impacts).

Jovian Early Bombardment and planetary migration.

The formation of Jupiter is the sole necessary condition to trigger the Jovian Early Bombardment, yet migration can play an important role in enhancing its effects due to the sweeping of the resonances through the asteroid belt (Turrini et al. 2011, 2012).

Planetary migration significantly reduces the flux of cometary impactors in the inner Solar System (Jupiter is more efficient in capturing or ejecting the planetesimals) but it also significantly increase the flux of asteroidal impactors (see Figs. 6 and 7 and Turrini et al. 2011, 2012).

Jovian Early Bombardment and catastrophic impacts.

Due to the short duration of the Jovian Early Bombardment, the probability of planetesimals undergoing a catastrophic impact are quite limited.

As shown in Fig. 6, the only planetesimals that have a significant chance of being disrupted during the Jovian Early Bombardment are 100 km-large bodies, in agreement with the current understanding of the collisional evolution of asteroids (see e.g. O'Brien & Sykes 2011).

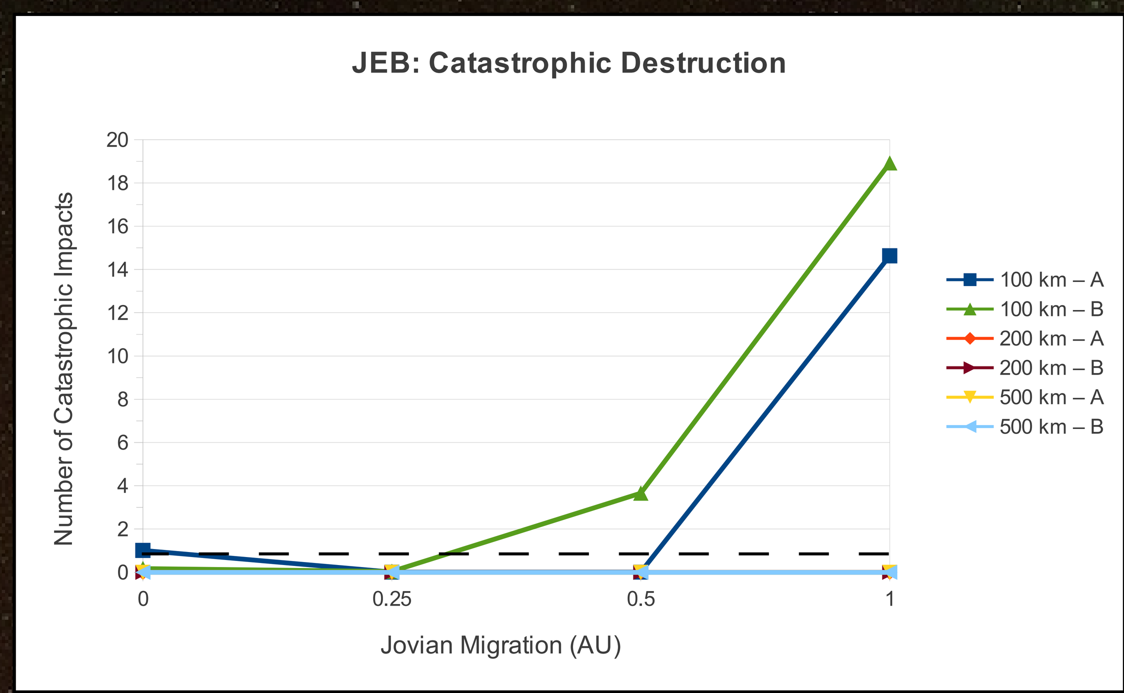

Figure 6: Cumulative number of catastrophic impacts that can be experienced by planetesimals of different size located at 2.30 AU (label "A") and 2.65 AU (label "B"). The dashed line indicates a cumulative number of catastrophic impacts equal to 1. Jupiter is assumed to end its migration at its present orbital position. The figure is based on the data reported in Turrini et al. (2012) for the size-frequency distribution by Coradini et al. (1981).

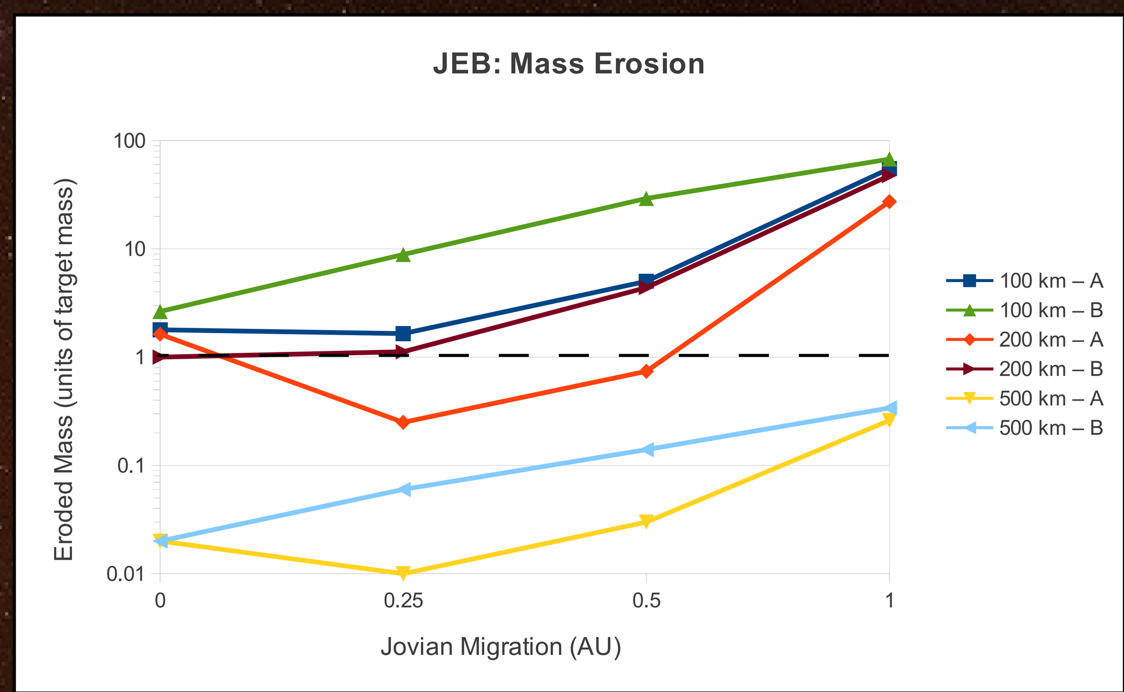

Figure 7: Cumulative mass loss (expressed in units of the target mass) due to cratering erosion that can be experienced by planetesimals of different size located at 2.30 AU (label "A") and 2.65 AU (label "B"). The dashed line indicates a cumulative mass loss equal to the target mass. Jupiter is assumed to end its migration at its present orbital position. The figure is based on the data reported in Turrini et al. (2012) for the size-frequency distribution by Coradini et al. (1981).

Jovian Early Bombardment and cratering erosion.

During the Jovian Early Bombardment, the collisional evolution of planetesimals is dominated by the process of cratering erosion (Davis et al. 1979; Turrini et al. 2012).

The cumulative mass loss due to cratering is large enough to destroy planetesimals with diameter of 200 km and can affect also planetesimals as big as 500 km (see Fig. 7 and Turrini et al. 2012).

As shown in Fig. 7, planetary migration and the sweeping of the resonances it causes can significantly increase the efficiency of cratering erosion in destroying the planetesimals during the Jovian Early Bombardment (Turrini et al. 2012).

Toward the Primordial Heavy Bombardment.

The processes triggering the Jovian Early Bombardment are general to all planetary system where giant planets are forming.

Generalizing the case of the Solar System, the formation of a giant planet in a circumstellar disk causes a Primordial Heavy Bombardment (Coradini et al. 2011, Turrini et al. 2012).

The formation of multiple giants planets, moreover, influences the duration of the Primordial Heavy Bombardment and can extend it beyond 1 Ma (Coradini et al. 2011, Turrini et al. 2012).

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