Reviewing the Grand Tack: Accurate Masses for Mars and the Asteroid Belt

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Overview

1. Classical in-situ planet formation theories fail to reproduce the small masses of Mars and the Asteroid Belt
2. A solution is given by a truncated inner disk, as shown in [Hansen, 2009]
3. The Grand Tack provides this truncation via Jupiter's and Saturn's migration through the disk

Introduction

- Many gas giants were discovered in the last decade which orbit their stars at extremely close distances. Planetary formation can not explain how gas giants are able to form inside of the Ice Line, where their gas would have been blown away by solar wind and radiation pressure. Thus, planetary migration was introduced; mechanisms which planets can use to change their distance to their stars, usually inwards.
- Most computer simulations that tried to reconstruct how our own solar system came to be failed to recreate its current state; planetesimals accreted in the asteroid belt, which had a few magnitudes more mass, and Mars usually was much bigger than it really is too. Varying the simulation's parameters helped; for example, a disk which is truncated to a small ring between 0.7 AU and 1.0 AU was able to recreate the small Mercury and Mars outside the ring, while keeping Venus and Earth inside it big.
- The Grand Tack Model delivers an explanation to this. Jupiter wanders inwards and takes the solid objects in its vicinity with it. Saturn begins its much faster migration later and catches up with Jupiter, which at this moment has compressed the planetesimal disk into a small ring. When Saturn's and Jupiter's orbital periods reach a resonance, their inwards movement stops and reverts - the Tack happens.

Migration

- Type I migration
  - Applies to small, terrestrial-mass-objects. By exciting density waves in the gas disk, they lose angular momentum and move towards their host star. Their fast migration poses a risk for planetary formation.

$$\frac{da}{dt} = -(2.7 - 1.1x)\frac{M_p}{M_s}\frac{\Sigma a^2}{M_s}\frac{v_k}{h^2}$$

  - Here, h is the ratio of scale height H to orbital radius a, $h = \frac{H}{a}$ and x is the power-law coefficient in the surface density Σ; $x = -1.5$. v_k the Keplerian velocity, and M_p, M_s the masses of the planet respectively the star.
- Type II migration
  - Bigger planets are able to clear a gap in the gas disk and avoid Type I migration. They migrate together with the gas disk and therefore much slower.

$$\frac{da}{dt} = -\frac{3\nu}{2a}$$

  - ν is the disk viscosity. Type II migration depends only on the disk conditions and is independent of the planet's mass.
- Type III or runaway migration
  - Runaway migration works only for a small fraction of planets, which are not massive enough to fully clear a gap. The steep density gradient at the gap border leads to an exponentially accelerated migration. Type III migration depends on a differential equation:

$$\alpha(M_p - \delta m)\frac{da}{dt} + \beta\delta m\frac{d^2a}{dt^2} = T$$

  - α and β are constants, T is the (dominant) Lindblad torque, and δm is the mass deficit in the partial gap of the planet. Planets migrating via Type III migration have masses comparable to Saturn.

The tacking process

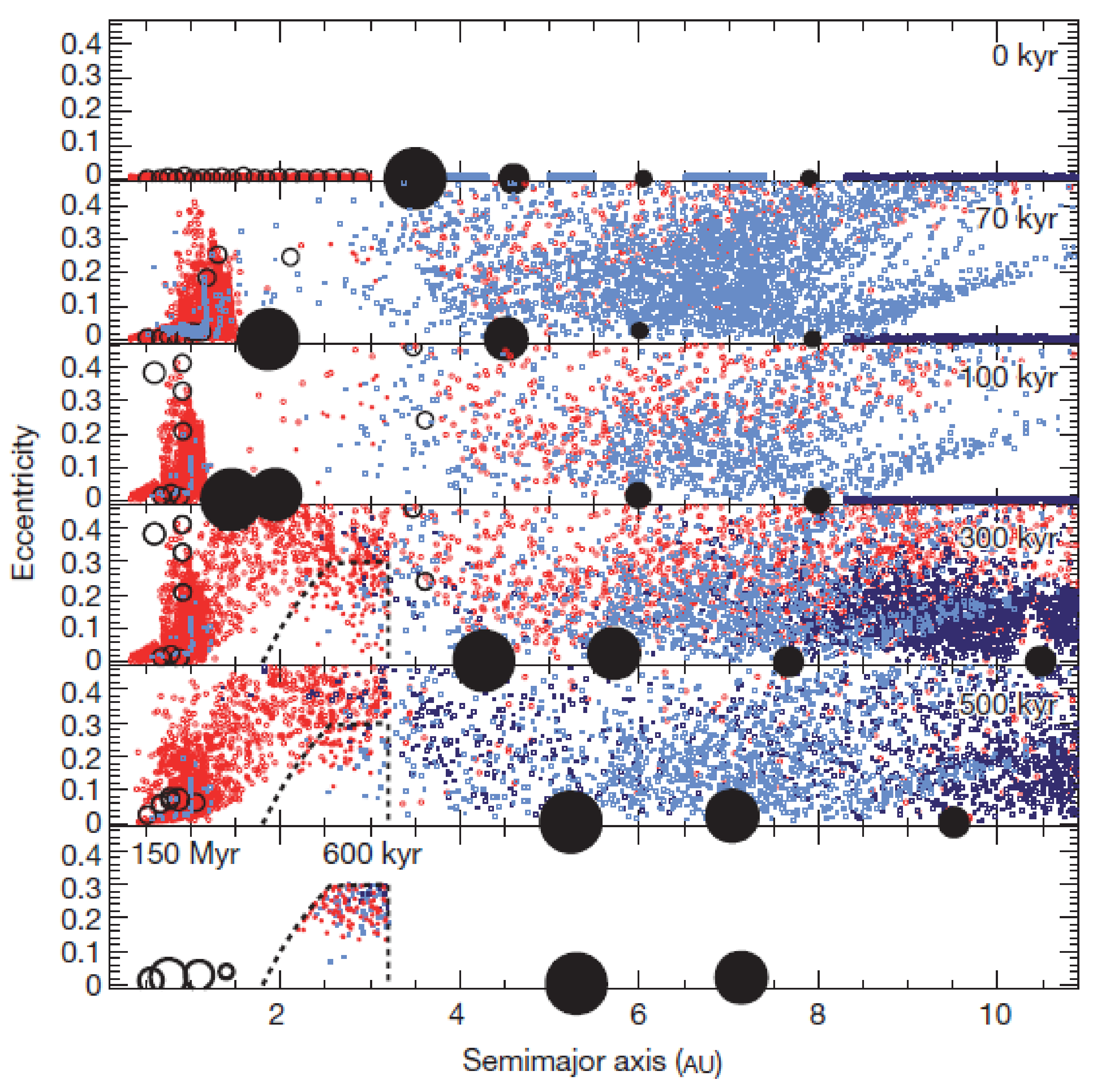

Figure 1:The solar system at different times during the Grand Tack, as postulated by [Walsh et al, 2011]. The black dots are the giant planets, red and blue ones indicate planetesimals poor respectively rich in volatile, icy material. Jupiter migrates via Type II inwards, Saturn follows later via Type III. Then, they migrate outwards via resonance trapping.

Simulations

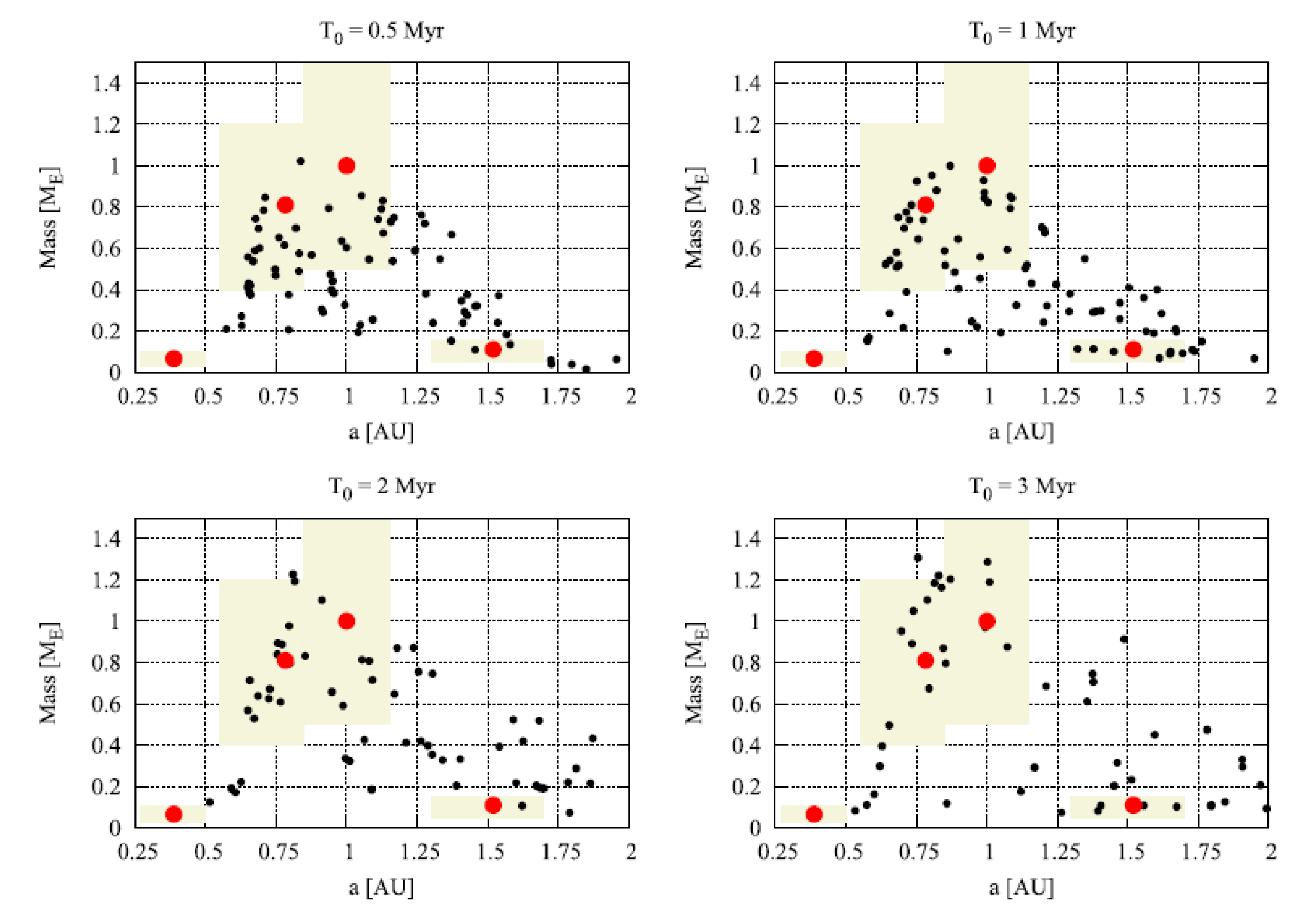

Figure 2:Results of simulations by [Brasser et al, 2016], incorporating Type I migration and with an unconventional tacking point of 2.0 AU. T_0 is the starting point of the simulation, indicating different stages of disk dissipation and planetary embryo growth. The diagrams show distance vs. mass of the resulting planets; the red dots are our actual terrestrial planets.

References

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