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Terrestrial planet formation constrained by the structure of the asteroid belt

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Abstract

Reproducing the large mass ratio between the Earth and Mars requires that the protoplanetary disk had a strong mass depletion in solids between roughly 1 AU and 3 AU. The Grand Tack model invokes a specific migration history of the giant planets of the Solar System to remove most of the mass initially beyond 1 AU and to leave the asteroid belt on an excited dynamical state. However, one could also invoke that a steep density gradient was created by the inward drift and pile-up of a large amount of small particles induced by gas-drag. Using a series of N-body numerical simulations in disks with steep surface density profiles we show that that disks with shallow density gradients reproduce the dynamical excitation of the asteroid belt by gravitational self-stirring, but inevitably form Mars analogs that are significantly more massive than the real planet. In contrast, a disk with a surface density gradient proportional to $r^{-5.5}$ beyond 1 AU reproduces the Earth/Mars mass ratio but leaves the asteroid belt in a dynamical state that is far colder than the real belt. We conclude that a steep mass distribution in the protoplanetary disk cannot produce the inner solar system. Thus, the asteroid belt has to have been depleted and dynamically excited by an external agent as, for instance, in the Grand Tack scenario.

1. Introduction

In classical numerical simulations, the assembly of the terrestrial planets is simulated from the accretion of Moon-mass to Mars-mass planetary embryos and smaller planetesimals orbiting between ∼0.5 and ∼4 AU [1]. This scenario has been proven successful in producing a variety of constraints as for example: Earth and Venus analogs, accounting for the origin of Earth's water and its accretion within the timescale consistent with radioactive chronometers [2]. Despite these appealing achievements, classical simulations also suffer from some important drawbacks. One of the most important ones is that the planet formed around 1.5 AU is about 5-10 time more massive than the real planet in these simulations [3]. One solution to the so-called "Mars problem" is to invoke that the terrestrial planets formed from a narrow annulus, with a steep mass density gradient beyond 1 AU [4].

The Grand Tack model [5] invokes a specific migration history of Jupiter and Saturn during the gas-disk phase to remove most of the mass initially beyond 1 AU, creating a narrow annulus of mass around 1 AU, and to leave the asteroid belt on an excited dynamical state. An alternative to the Grand Tack scenario to produce the confined disk and a mass deficient asteroid belt could be invoke that a lot of solid material drifted to within 1 AU by gas drag, leaving the region beyond 1 AU substantially depleted in mass. This idea is very appealing in a broad context of planet formation. This is because it is often invoked to produce a large pile-up of mass in the inner disk to explain the formation of close-in super-Earths (eg. [6-7]). Therefore, the goal of this paper is to test whether any of these gradients could explain at the same time the small mass of Mars and the properties of the asteroid belt (mass deficit and inclination excitation).

2. Methods

The simulations presented in this paper fit in the context of the classical scenario of terrestrial planet formation. We perform simulations starting from disks with a wide range of surface density profiles. We tested disks with surface density profiles given by $\Sigma_1 r^{-x}$, where x = 2.5, 3.5, 4.5 or 5.5 and r is the heliocentric distance. Σ_1 is the solid surface density at 1 AU. Our disks extends from 0.7 to 4 AU. We adjusted Σ_1 to fix the total mass in the disk between 0.7 and 4 AU at $2.5M_{\oplus}$, comparable to the sum of the masses of the terrestrial planets. Our simulations also included fully-formed Jupiter and Saturn on orbits consistent with the latest version of the Nice Model [8]. During our simulations, we neglect gas drag and gas-induced migration of the planetary embryos.

3. Results

Our results show that steeper disks (higher x) produce smaller planets around 1.5 AU. This is to be expected since steeper disks have less mass in their outer parts (for a fixed disk mass). Therefore, they are closer to the idealized initial conditions proposed by [4], namely a disk truncated at 1 AU. The simulations with x of 2.5, 3.5 and 4.5 do not reproduce the terrestrial planets because they produce planets at around 1.5 AU that are systematically too massive compared to Mars. Only our steepest disk profiles (x = 5.5) produced good Mars analogs, but those simulations yielded an under-excited asteroid belt. Simulations with flatter disk profiles formed Mars analogs far more massive than the actual planet. Those simulations excited the asteroid belt to roughly the right amount but failed to adequately match observations because too many embryos were stranded in the belt, for example.

4. Conclusions

Using a series of simulations of terrestrial planet formation in disks with steep surface density profiles we show that the asteroid belt orbital excitation provides a crucial constraint against the inward migration and pile up pf small particles induced by gas-drag, for the solar system. Simulations with a surface density gradient proportional to $r^{-5.5}$ can indeed to reproduce the Earth/Mars mass ratio, but leaves the asteroid belt on a dynamical state way too cold compared to the real belt. In contrast, shallow density gradients allow the dynamical excitation of the asteroid belt by a self-stirring process, but lead inevitably to the formation of a Mars analog which is significantly more massive than the real planet.

We find the small mass of Mars and the dynamical excitation of the asteroid belt have diametrically opposite scalings; Mars' small mass requires a mass deficit but producing asteroids with inclinations above ~ 10 degrees requires a significant amount of mass in embryos. Therefore, we conclude that no disk profile can explain at the same time the structure of the terrestrial planet system and of the asteroid belt. Thus, the asteroid belt has to have been depleted and dynamically excited by an external agent as, for instance, in the Grand Tack scenario.

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