WHY IS MARS SMALL? A NEW TERRESTRIAL PLANET FORMATION MODEL INCLUDING PLANETESIMAL-DRIVEN MIGRATION.

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Motivation. The small size of Mars is a persistent problem for models of terrestrial planet formation. Simulations that assume a continuous distribution of planetary embryos throughout the terrestrial planet and asteroid belt regions consistently produce Mars analogues that are 3–$10\times$ too massive [1, 2]. Low mass Mars analogues have only ever been produced in simulations with adhoc or implausible initial conditions, for instance when Jupiter and Saturn are given very high eccentricities [3], or all planet-forming materials are restricted to a narrow annulus between 0.7–1.0 AU [4]. Here we present new simulations that explain the small size of Mars by including the effect of planetesimal-driven migration, a critical mechanism that has been left out of studies of the early stages of embryo formation.

Embryo growth with migration. Planetesimal-driven migration is a well-known phenomenon in studies of the evolution of giant planet orbits [5–8], and arises from the asymmetric scattering by a large body embedded in a disk of much smaller planetesimals [9]. The primary reason that planetesimal-driven migration has been neglected in the study of terrestrial planet formation is limitations in computing power. In the earliest stages of planet formation, the protoplanetary disk is primarily composed of < 100 km planetesimals [10, 11]. Simulating such a disk that spans the entire terrestrial planet region is impractical. The earliest stages of planet formation are therefore modeled analytically or semi-analytically [12–14], or by applying N-body codes to isolated, narrow sections of the disk [15, 16]. Unfortunately, the limitations of these techniques are such that planetesimal-driven migration has not been seen.

There are two main limitations in the earlier studies that have prevented migration of embryos from occurring in those simulations. The first is a problem of resolution. We find that migration is only seen in simulations where the ratio between the mass of the embryo or planet and a typical planetesimal in the disk is $\gtrsim 100$. In a terrestrial planet simulation, this requires a large number of simulated planetesimals in order to properly model the full disk, and typically simulations involving embryos embedded in planetesimal disks use planetesimals only as small as $1/40$ the mass of the embryos [2].

The second limitation involves assumptions about how embryos are initially distributed in the protoplanetary disk. Planetesimal-driven migration of embryos will also only occur if an embryo is able to migrate through an embryo-free zone of the disk. In the late-accretion stage, where typically the full terrestrial planet disk is modeled, simulations take as their initial conditions a situation in which all embryos throughout the terrestrial planet region have formed simultaneously [1–3]. However, this assumption is incorrect.

Embryo formation is expected to happen in an "inside-out" fashion, that is the first embroys form in the inner-most part of the disk before they form in the outermost part [17]. Initially a population of embryos will form inward of 1 AU in the standard way due to runaway growth [12,13]. When the outermost embryo in the population grows to a mass $\sim 100\times$ the mass of a typical planetesimal in the disk, planetesimal-driven migration will be occur. The outermost embryo will then migrate away from the rest of the population, and outward migration is self-sustaining once it starts [9].

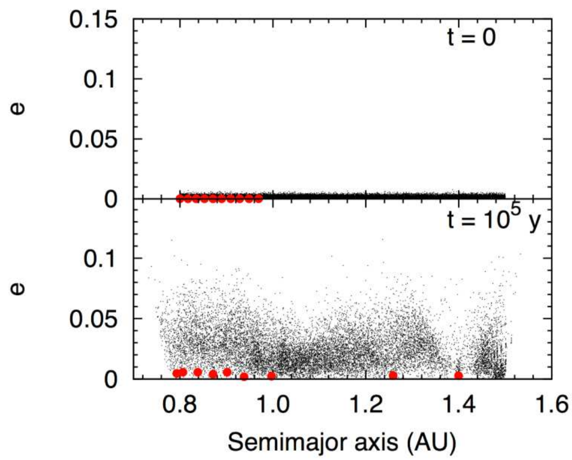

Figure 1: Migrating embryos in a $2\times$MMSN planetesimal disk. The red circles are embryos with initial masses of 0.1 Mars-mass. The black circles are planetesimals with initial masses $1/150$ that of the embryos. Only 1 of every 5 planetesimals is plotted here.

To investigate the effect of planetesimal-driven migration on embryo growth, we have simulated test cases involving embryos embedded in disks of planetesimals using the N-body code SyMBA [18]. In all of our simulations, the planetesimal disk is given Rayleigh distributions of eccentricity and inclination with root mean squares values of $\langle \bar{e} \rangle = 2\langle \sin \bar{i} \rangle = 2 \times 10^{-3}$ and surface mass density distribution given by $\Sigma = f \cdot 8 \text{ g cm}^{-2}(a/\text{ AU})^{-1.5}$, where $f = 1$ corresponds to the standard minimum mass solar nebula for the inner solar system [19]. Planetesimals interact gravitationally with embryos, but not with each other. In our first simulation we assume that a population of ten 0.01 $\mathrm{M}_\oplus$ embryos has formed between 0.8–1.0 AU before planetesimal-driven migration becomes important, but that the planetesimal disk spans from 0.8–1.5 AU. This distribution of embryos and planetesimals approximates the inside-out embryo formation process in the region between Earth and

Mars. Figure 1 shows an example of how a small number of embryos (in this case, two) that form near 1 AU will migrate outward to the region of Mars.

A result of this and other simulations we have performed is that a lunar mass embryo in a $1\times$MMSN rocky planetesimal disk at 1 AU will migrate with a rate of ~ 4 AU My^{-1}. Meanwhile, its mass growth rate due to migration is $\sim 1\ \mathrm{M}_\oplus\ \mathrm{My}^{-1}$. This is roughly two orders of magnitude faster than the oligarchic growth rate for the same lunar-mass object [20], and while the oligarchic growth rate slows down as the embryo grows, the mass growth due to migration is nearly constant. This is because, in the standard picture of a static embryo in a disk, the embryo locally depletes its feeding zone of material as it grows. In contrast, a migrating embryo is always supplied fresh planetesimals as it moves through the dynamically cold disk that is driving its migration. Therefore, an embryo undergoing planetesimal-driven migration can rapidly grow to planetary size, as long as nothing hinders its ability to continue to migrate.

The migration rate of the outermost embryo through the embryo-free disk is rapid relative to the timescale for new embryos to form, so this object will become the dominant body in the outer terrestrial planet region. Critically, the embryo bypasses the standard oligarchic to late-accretion stages and grows to Mars-size. The Mars-mass embryo will be isolated from other embryos by a dynamically excited planetesimal disk, protecting it from further growth by embryo mergers during the late-accretion stage.

Halting migration and making Mars. In order to make Mars in its present orbit at its present mass, something must stop its migration. The migration rate is sensitive to the surface mass density of the planetesimal disk. Migration will be greatly hindered when the mass ratio between the embryo and the collective mass of planetesimals that the embryo is scattering rises above ~ 2 [9]. Most obviously, this halting condition can occur if the embryo reaches an edge or a gap in the planetesimal disk. In our first simulation, shown in Figure 1, the planetesimal disk had an edge at 1.5 AU to stop the migration of the outermost embryo. However, the halting condition may also be met due when when the embryo grows to a threshold mass relative to the local surface mass density of the planetesimal disk. In a $1\times$MMSN planetesimal disk at 1.5 AU, this halting condition will occur for a Mars-mass embryo.

We performed another simulation demonstrating how an embryo naturally halts at the orbital distance and mass of Mars, with results shown in Figure 2. In this simulation, a 0.1 Mars-mass embryo begins at 1.0 AU. A $1\times$MMSN planetesimal disk extends from 0.9 AU out to 1.8 AU.

Implications. We hypothesize that Mars is an "escaped embryo" that migrated away from its birthplace inward of 1 AU. There it became isolated from the other planetary embryos that eventually merged to form Venus and Earth. The initial conditions used in late-stage accretion simulations assume incorrectly that embryos have a compositions that reflect their position in the disk [3]. We show here that embryos can move quite far from their birth place. Planet formation studies also assume that the growth history of planets follows an orderly path: Embryos form in the runaway and oligarchic growth stages, and planets form in the late-accretion stage in embryo mergers. We show that some bodies may bypass these stages, and through migratory growth form planet-sized objects directly.

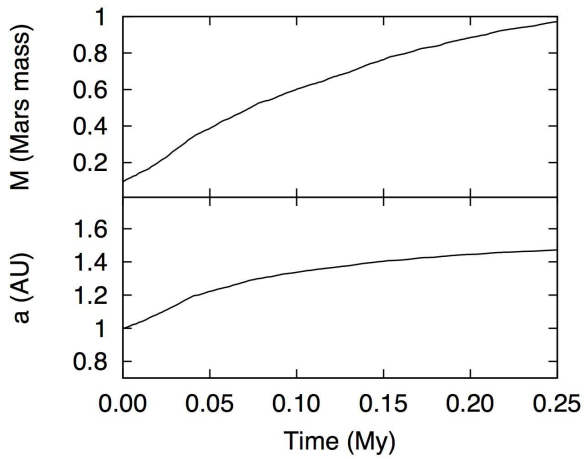

Figure 2: Mass and semimajor axis as a function of time for a lunar mass embryo migrating in a $1\times$MMSN planetesimal disk.

References

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