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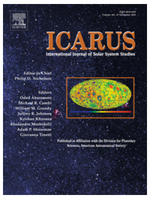

Mars' growth stunted by an early giant planet instability

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ABSTRACT

Many dynamical aspects of the solar system can be explained by the outer planets experiencing a period of orbital instability sometimes called the Nice Model. Though often correlated with a perceived delayed spike in the lunar cratering record known as the Late Heavy Bombardment (LHB), recent work suggests that this event may have occurred much earlier; perhaps during the epoch of terrestrial planet formation. While current simulations of terrestrial accretion can reproduce many observed qualities of the solar system, replicating the small mass of Mars requires modification to standard planet formation models. Here we use 800 dynamical simulations to show that an early instability in the outer solar system strongly influences terrestrial planet formation and regularly yields properly sized Mars analogs. Our most successful outcomes occur when the terrestrial planets evolve an additional 1–10 million years (Myr) following the dispersal of the gas disk, before the onset of the giant planet instability. In these simulations, accretion has begun in the Mars region before the instability, but the dynamical perturbation induced by the giant planets' scattering removes large embryos from Mars' vicinity. Large embryos are either ejected or scattered inward toward Earth and Venus (in some cases to deliver water), and Mars is left behind as a stranded embryo. An early giant planet instability can thus replicate both the inner and outer solar system in a single model.

1. Introduction

It is widely understood that the evolution of the solar system's giant planets play the most important role in shaping the dynamical system of bodies we observe today. When the outer planets interact with an exterior disk of bodies, Saturn, Uranus and Neptune tend to scatter objects inward (Fernandez and Ip, 1984). To conserve angular momentum through this process, the orbits of these planets move outward over time (Hahn and Malhotra, 1999; Gomes, 2003). Thus, as the young solar system evolved, the three most distant planets' orbits moved out while Jupiter (which is more likely to eject small bodies from the system) moved in. To explain the excitation of Pluto's resonant orbit with Neptune, Malhotra (1993) proposed that Uranus and Neptune must have undergone significant orbital migration prior to arriving at their present semi-major axes. Malhotra (1995) later expanded upon this idea to explain the full resonant structure of the Kuiper belt. In the same manner, an orbital instability in the outer solar system can successfully excite Kuiper belt eccentricities and inclinations, while simultaneously moving the giant planets to their present semi-major axes via planet-planet scattering followed by dynamical friction (Thommes et al., 1999).

These ideas culminated in the eventual hypothesis that, as the giant planets orbits diverged after their formation, Jupiter and Saturn's orbits would have crossed a mutual 2:1 Mean Motion Resonance (MMR). Known as the Nice (as in Nice, France) Model (Tsiganis et al., 2005; Gomes et al., 2005; Morbidelli et al., 2005), this resonant configuration of the two most massive planets causes a solar system-wide instability, which has been shown to reproduce many peculiar dynamical traits of the solar system. This hypothesis has subsequently explained the overall structure of the Kuiper belt (Levison et al., 2008; Nesvorný, 2015a; 2015b), the capture of trojan satellites by Jupiter (Morbidelli et al., 2005; Nesvorný et al., 2013), the orbital architecture of the asteroid belt (Roig and Nesvorný, 2015), and the giant planets' irregular satellites, including Triton (Nesvorný et al., 2007).

The Nice Model itself has changed significantly since its introduction. In order to keep the orbits of the terrestrial planets dynamically cold (low eccentricities and inclinations), Brasser et al. (2009) proposed that Jupiter "jump" over its 2:1 MMR with Saturn, rather than migrate smoothly through it (Morbidelli et al., 2009a; 2010). Otherwise, the terrestrial planets were routinely excited to the point where they were ejected or

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collided with one another in simulations. The probability of producing successful jumps in these simulations is greatly increased when an extra primordial ice giant was added to the model (Nesvorný, 2011; Batygin et al., 2012). In successful simulations, the ejection of an additional ice giant rapidly forces Jupiter and Saturn across the 2:1 MMR. Furthermore, hydrodynamical simulations (Snellgrove et al., 2001; Papaloizou and Nelson, 2003) show that a resonant chain of giant planets is likely to emerge from the dissipating gaseous circumstellar disk, with Jupiter and Saturn locked in an initial 3:2 MMR resonance (Masset and Snellgrove, 2001; Morbidelli and Crida, 2007; Pierens and Nelson, 2008). This configuration can produce the same results as the 2:1 MMR crossing model (Morbidelli et al., 2007). In this scenario, the instability ensues when two giant planets fall out of their mutual resonant configuration. Such an evolutionary scheme seems consistent with the number of resonant giant exoplanets discovered (eg: HD 60532b, GJ 876b, HD 45364b, HD 27894, Kepler 223 and HR 8799 (Holman et al., 2010; Fabrycky and Murray-Clay, 2010; Rivera et al., 2010; Delisle et al., 2015; Mills et al., 2016; Trifonov et al., 2017)).

Despite the fact that 5 and 6 primordial giant planet configurations are quite successful at reproducing the architecture of the outer solar system (Nesvorný and Morbidelli, 2012), delaying the instability ∼400 Myr to coincide with the lunar cataclysm (Gomes et al., 2005) still proves problematic for the terrestrial planets. Indeed, Kaib and Chambers (2016) find only a ∼1% chance that the terrestrial planets' orbits and the giant planets' orbits are reproduced simultaneously. Even in systems with an ideal "jump," the eccentricity excitation of Jupiter and Saturn can bleed to the terrestrial planets via stochastic diffusion, leading to the over-excitation or ejection of one or more inner planets (Agnor and Lin, 2012; Brasser et al., 2013; Roig and Nesvorný, 2015). It should be noted, however, that Mercury's uniquely excited orbit (largest mean eccentricity and inclination of the planets) may be explained by a giant planet instability (Roig et al., 2016). Nevertheless, the chances of the entire solar system emerging from a late instability in a configuration roughly resembling its modern architecture are very low (Kaib and Chambers, 2016). This suggests that the instability is more likely to have not occurred in conjunction with the LHB, but rather before the terrestrial planets had fully formed. Fortunately, many of the dynamical constraints on the problem are fairly impartial to whether the instability happened early or late (Morbidelli et al., 2018). The Kuiper belt's orbital structure (Levison et al., 2008; Nesvorný, 2015a; 2015b), Jupiter's Trojans (Morbidelli et al., 2005; Nesvorný et al., 2013), Ganymede and Callisto's different differentiation states (Barr and Canup, 2010) and the capture of irregular satellites in the outer solar system (Nesvorný et al., 2007) are still explained well regardless of the specific timing of the Nice Model instability. In addition to perhaps ensuring the survivability of the terrestrial system, there are several other compelling reasons to investigate an early instability:

1. **Uncertainties in disk properties**: Since the introduction of the Nice Model, simplifying assumptions of the unknown properties of the primordial Kuiper belt have provided initial conditions for N-body simulations. The actual timing of the instability is highly sensitive to the particular disk structure selected (Gomes et al., 2005). Furthermore, numerical studies must approximate the complex disk structure with a small number of bodies in order to optimize the computational cost of simulations. In fact, most N-body simulations do not account for the effects of disk self gravity (Nesvorný and Morbidelli, 2012). When the giant planets are embedded in a disk of gravitationally self-interacting particles using a graphics processing unit (GPU) to perform calculations in parallel and accelerate simulations (Grimm and Stadel, 2014), instabilities typically occur far earlier than what is required for a late instability (Quarles & Kaib, in prep).

2. **Highly siderophile elements** (**HSE**): A late instability (the LHB) was originally favored because of the small mass accreted by the Moon relative to the Earth after the Moon-forming impact (for a review of these ideas see Morbidelli et al. (2012)). The HSE record from lunar samples indicates that the Earth accreted almost 1200 times more material, despite the fact that its geometric cross-section is only about 20 times that of the Moon (Walker et al., 2004; Day et al., 2007; Walker, 2009). Thus, the flux of objects impacting the young Earth would have had a very top-heavy size distribution (Bottke et al. (2010), however Minton et al. (2015) showed that the pre-bombardment impactor size distribution may not be as steep as originally assumed). This distribution of impactors is greatly dissimilar from what is observed today, and favors the occurrence of a LHB. New results, however, indicate that the HSE disparity is actually a result of iron and sulfur segregation in the Moon's primordial magma ocean causing HSEs to drag towards the core long after the moon-forming impact (Rubie et al., 2016). Because the crystallization of the lunar magma took far longer than on Earth, a large disparity between the HSE records is expected (Morbidelli et al., 2018).

3. **Updated impact data**: The LHB hypothesis gained significant momentum when none of the lunar impactites returned by the Apollo missions were older than 3.9 Gyr (Tera et al., 1974; Zellner, 2017). However, recent $^{40}Ar/^{39}Ar$ age measurements of melt clasts in Lunar meteorites are inconsistent with the U/Pb dates determined in the 1970s (Fernandes et al., 2000; Chapman et al., 2007; Boehnke et al., 2016). These new dates cover a broader range of lunar ages; and thus imply a smoother decline of the Moon's cratering rate. Furthermore, new high-resolution images from the Lunar reconnaissance Orbiter (LRO) and the GRAIL spacecraft have significantly increased the number of old (>3.9 Gyr) crater basins used in crater counting (Spudis et al., 2011; Fassett et al., 2012). For example, samples returned by Apollo 17 that were originally assumed to be from the impactor that formed the Serenitatis basin are likely contaminated by ejecta from the Irbrium basin (Spudis et al., 2011). Because the Serenitatis basin is highly marred by young craters and ring structures, it is likely older than 4 Gyr, and the Apollo samples are merely remnants of the 3.9 Gyr Irbrium event.

Here we build upon the hypothesis of an early instability by systematically investigating the effects of the Nice Model occurring during the process of terrestrial planetary formation. Since advances in algorithms substantially decreased the computational cost of N-body integrators in the 1990s (Wisdom and Holman, 1991; Duncan et al., 1998; Chambers, 1999), many papers have been dedicated to modeling the late stages (giant impact phase) of terrestrial planetary formation. Observations of proto-stellar disks (Haisch et al., 2001; Pascucci et al., 2009) suggest that free gas disappears far quicker than the timescale radioactive dating indicates it took the terrestrial planets to form (Halliday, 2008; Kleine et al., 2009). Because the outer planets must clearly form first, the presence of Jupiter is supremely important when modeling the formation of the inner planets (Wetherill, 1996; Chambers and Cassen, 2002; Levison and Agnor, 2003a). Early N-body integrations of planet formation in the inner solar system in 3 dimensions from a disk of planetary embryos and a uniformly distributed sea of planetesimals reproduced the general orbital spacing of our 4 terrestrial planets (Chambers and Wetherill, 1998; Chambers, 2001). However, these efforts systematically failed to produce an excited asteroid belt and 4 dynamically cold planets with the correct mass ratios (Mercury and Mars are ∼5% and ∼10% the mass of Earth respectively).

Numerous subsequent authors approached these problems using various methods and initial conditions. By accounting for the dynamical friction of small planetesimals, O'Brien et al. (2006) and Raymond et al. (2006) more consistently replicated the low