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Jupiter's role in sculpting the early Solar System

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Recent observations made by the Kepler space mission, combined with statistical analysis of existing ground and space-based data, have shown that planets somewhat bigger than the Earth—but substantially smaller than Jupiter—are extremely common in our Galaxy (1–4). These systems are typically found to be tightly packed, nearly coplanar, and have nearly circular orbits. Furthermore, these planets tend to have very short-period orbits, ranging from days to months. In contrast, our innermost planet, Mercury, orbits the Sun once every 88 d. Thus, taken at face value, these observations imply that the architecture of our Solar System is unique compared with the galactic population. In other words, why are there no short-period planets in our Solar System? In PNAS, Batygin and Laughlin (5) demonstrate that Jupiter is to blame. In particular, Jupiter's inward-followed-by-outward migration during the Solar System's early evolution could have driven a collisional cascade that would grind planetesimals to smaller size. Gas drag, which dominates these small planetesimals, may then have driven preexisting short-period planets into the Sun. Thus, Batygin and Laughlin (5) suggest that the terrestrial planets in our Solar System are in fact "second-generation planets," which formed after the first short-period planets were destroyed, in mass-dispersed, gas-depleted conditions (see Fig. 1 for the description of the scenario). The developed model suggests that systems with short-period Earth and super-Earth planets are anticorrelated with the existence of giant planets within the same system.

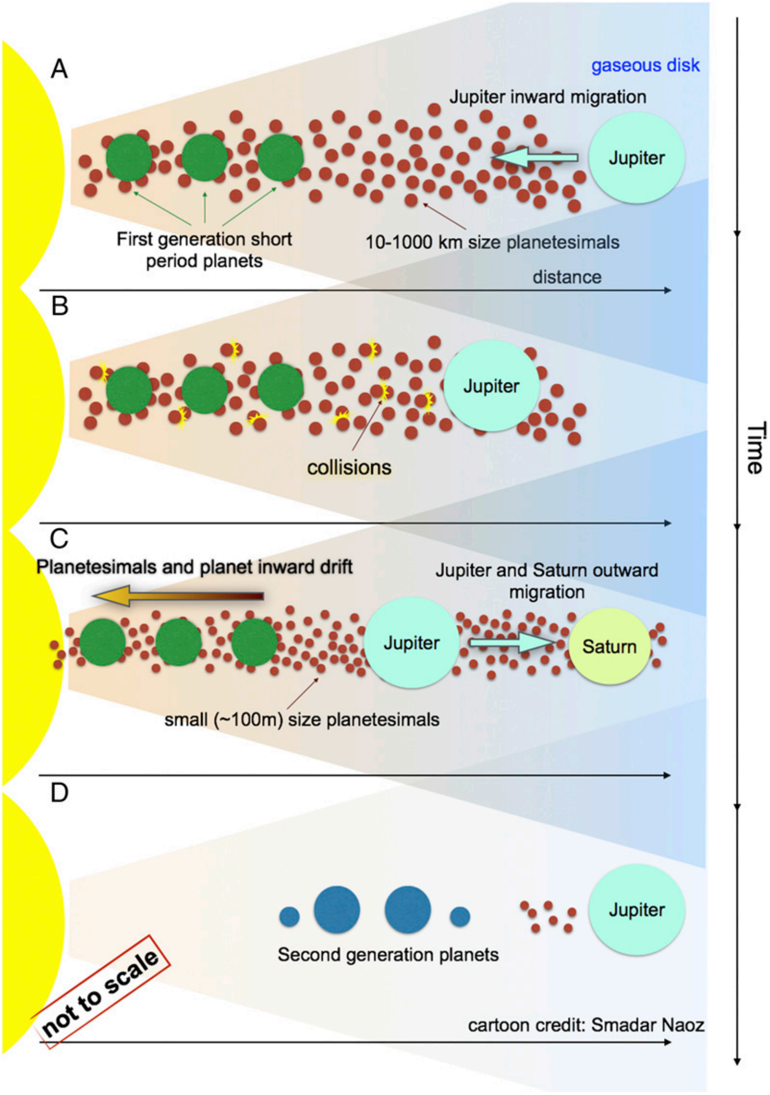

Fig. 1. Description of the early Solar System evolution. (*A*) The initial setting of this model includes the short-period planets (as observed in many exoplanets). At that stage Jupiter starts to migrate inward. (*B*) Jupiter's migration captures the planetesimals into resonance, which cause them to cross orbit and collide with each other. (*C*) The resulted collisional cascade grinds the planetesimals below critical size of 100 m and aerodynamics drag them into the Sun. The first generation of planets will be carried into the Sun by these inward-drifting debris. (*D*) The destruction of the first generation of planets leaves behind a mass- and gas-depleted narrow annulus out of which the terrestrial planets can now form.

The standard model for the formation of terrestrial planets, in combination with cosmochemical evidence of astrophysical processes, suggests that planetesimals formed about 100–200 Myr before the final assembly of the terrestrial planets took place (6–8). In other words, the fundamental planetary building blocks (i.e., planetesimals) were generated ~1 Myr after the Sun was born, but terrestrial planet formation took about 100–200 Myr. At that time most of the gas in the disk had already dispersed, which may explain the low-mass atmospheres of the Solar System's terrestrial planets. This theory is, however, at odds with the observations of the possibly large gaseous atmospheric

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envelope of extrasolar super-Earths and Earth-like planets.

To add to this puzzle, the small masses of Mars and Mercury point toward the possibility that the terrestrial planets formed from a narrow annulus that spanned over 0.5- to 1-y orbital periods around the Sun (9). The outer edge of such an annulus can be the result of the aforementioned inward-followed-by-outward migration of Jupiter (10). The inward portion of Jupiter's orbital excursion arises from gravitational interactions between a single planet and a gaseous disk (11). The planet perturbs the disk by exciting spiral density waves in the disk; thus, the disk and the planet exchange angular momentum. This process repels gas away from the planet's orbit, and eventually Jupiter carves out a substantial gap in the protosolar nebula. Positioning itself at the center of the gap, Jupiter drifts inward, along with the accretionary flow of the gas (Fig. 1*A*). An additional migrating planet can, in some cases, be captured into resonance with the inner planet. In such a configuration the period ratio of the two planets is given approximately by the ratio of consecutive integers. Angular momentum is then exchanged between the planets and will force them to keep this ratio. For a less-massive exterior planet, this may result in an outward migration of both planets (12).

This model, known as the "Grand Tack," has been suggested to have taken place during the formation of the Solar System (10). It is able to explain the architecture of the terrestrial and giant planets as well as the astroids (10, 13). Furthermore, the model provides a natural mechanism for the delivery of water to the terrestrial planets (14). Batygin and Laughlin (5) explore the consequences of the Grand Tack model on the surrounding planetesimals and on short-period preexisting planets, and thus place our Solar System in the Galactic context.

During Jupiter's inward migration, a substantial fraction of planetesimals will find themselves swept by rational period ratios with Jupiter. These objects consequently lock into resonance with Jupiter, which forces them to maintain the same period ratio (similarly to resonant capture of two planets). Therefore, planetesimals will migrate inward and their orbits will become more elliptical (15, 16). Accordingly, these planetesimals will cross each other's orbits and will start to experience collisions (Fig. 1*B*); this triggers a collisional cascade between the planetesimals, which grinds them to smaller and smaller sizes. Batygin and Laughlin (5) demonstrate that this mechanism affects planetary building blocks in the disk whose size exceeds $\sim$10 km, and leads to an efficient mode of collisional grinding. It is worth noting that the actual process of this resonant-forced collisional cascade is rather complicated; however, once the planetesimals become smaller than a critical size (<100 m for 1-y planetesimal orbit) aerodynamic drag induces rapid orbital decay that removes them from Jupiter's resonant region and drives them into the Sun (17).

> **Batygin and Laughlin suggest that the terrestrial planets in our Solar System are in fact "second-generation planets," which formed after the first short-period planets were destroyed.**

If there are short-period planets that are present during the epoch of Jupiter's inward migration, they will be carried into the Sun by inward-drifting debris. To this end, the simulations of Batygin and Laughlin (5) showed that that gas drag is so efficient that even cumulative planetesimal mass of about an order-of-magnitude smaller than the super-Earths is enough to drive the planets into the Sun (Fig. 1*C*). Although it is still unclear if short-period extrasolar super-Earths formed in situ (18, 19) or migrated inward (20, 21), their overwhelming abundance within the Galaxy (1–4) allows one to reasonably hypothesize that they may have also formed in the Solar System. Correspondingly, Batygin and Laughlin (5) numerically simulate the evolution of a hypothetical system, with short-period planets on orbits similar to that of the well-known Kepler-11 system. The authors show that small-size planetesimals can indeed shepherd these short-period planets into the Sun.

This scenario yields the destruction of the first generation of planets and leaves behind a mass- and gas-depleted narrow annulus out of which the terrestrial planets can now form (Fig. 1*D*). This means that the formation of Earth and its neighbors has been sculpted by Jupiter's inward and outward migration. An immediate prediction is that the observed volatile-rich short-period planets are less likely to have a close-by giant planet.

The novelty of the model outlined by Batygin and Laughlin (5) resides in the fact that it naturally explains the missing short-period planets in our Solar System that seem to be so abundant in our Galaxy. It also connects the formation timescales between the inner and outer parts of the Solar System into one complete picture, thereby bringing us one step closer to a comprehensive model of conglomeration and evolution of planetary systems.

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