PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

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Review

Cite this article: Morbidelli A. 2014 Scenarios of giant planet formation and evolution and their impact on the formation of habitable terrestrial planets. *Phil. Trans. R. Soc. A* **372**: 20130072.
http://dx.doi.org/10.1098/rsta.2013.0072

One contribution of 17 to a Theo Murphy Meeting Issue 'Characterizing exoplanets: detection, formation, interiors, atmospheres and habitability'.

Subject Areas:
Solar System, extrasolar planets, astrobiology

Keywords:
giant planet migration, terrestrial planet accretion, habitability

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Scenarios of giant planet formation and evolution and their impact on the formation of habitable terrestrial planets

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In our Solar System, there is a clear divide between the terrestrial and giant planets. These two categories of planets formed and evolved separately, almost in isolation from each other. This was possible because Jupiter avoided migrating into the inner Solar System, most probably due to the presence of Saturn, and never acquired a large-eccentricity orbit, even during the phase of orbital instability that the giant planets most likely experienced. Thus, the Earth formed on a time scale of several tens of millions of years, by collision of Moon- to Mars-mass planetary embryos, in a gas-free and volatile-depleted environment. We do not expect, however, that this clear cleavage between the giant and terrestrial planets is generic. In many extrasolar planetary systems discovered to date, the giant planets migrated into the vicinity of the parent star and/or acquired eccentric orbits. In this way, the evolution and destiny of the giant and terrestrial planets become intimately linked. This paper discusses several evolutionary patterns for the giant planets, with an emphasis on the consequences for the formation and survival of habitable terrestrial planets. The conclusion is that we should not expect Earth-like planets to be typical in terms of physical and orbital properties and accretion history. Most habitable worlds are probably different, exotic worlds.

1. Introduction

The discovery of extrasolar giant planets has highlighted the great diversity of planetary systems. Whereas the giant planets of the Solar System are quite far from the Sun and have quasi-circular orbits, many extrasolar giant planets have orbits with small orbital semi-major

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axes, comparable to those of the terrestrial planets in our Solar System or even smaller. Moreover, many extrasolar giant planets have eccentric orbits, which are probably the relic of very violent past evolutions, characterized by mutual planetary encounters (see [1–3] for a non-exhaustive list of references). Moreover, it is becoming apparent that 30–50% of the solar-type stars are surrounded by systems of multiple super-Earth and Neptune-mass objects with orbital periods smaller than 100 days [4], often on quasi-circular and coplanar orbits with small mutual spacing. The origin of such great diversity of planetary systems probably stems from the masses of the largest planets that each protoplanetary disc is able to form and from the consequent planet migration patterns. Whereas the accretion of giant planets is still not well understood [5], the migration patterns as a function of planet masses and orbital configuration are now studied effectively with hydrodynamical simulations. Therefore, some general ideas have now emerged about the possible post-formation evolution of giant planet systems. Terrestrial planets near the habitable zone are not yet observable, particularly around solar-type stars. It is therefore interesting to discuss from the theoretical point of view the impact that the different giant planet evolution patterns may have on the formation and survival of terrestrial planets, while waiting for future observational ground truth. Such a discussion is the main goal of this paper. In §2, I start by reviewing our understanding of the evolution of the giant planets of our Solar System, and the impact that it had on the formation of the terrestrial planets. Then, in §3, I look at alternative evolutionary paths that can explain the diversity of the giant planet systems and make some educated guesses about the fate of terrestrial planets. The conclusions of this exercise are summarized in §3.

2. Understanding our Solar System

It is known that, in our Solar System, the giant planets formed well before the Earth. In fact, the giant planets accreted substantial amounts of hydrogen and helium, and therefore they should have completed their formation before the disappearance of the gas in the protoplanetary disc. From observations of discs around stars of known age, gas removal is inferred to happen within just a few million years [6] from stellar formation. By contrast, radioactive chronometers indicate that the Earth took 30–100 Myr to form (see [7] for a review). This consideration suggests that a good model of terrestrial planet formation should first address the formation and evolution of the giant planets, because the latter sets up the ‘environment’ in which the terrestrial planets eventually formed.

A striking characteristic of our Solar System is a clear division between the realm of terrestrial planets and that of giant planets. The terrestrial planets are close to the Sun and the giant planets are far away, with the asteroid belt in between. This characteristic is not typical of planetary systems. The detection of extrasolar planets, in fact, has shown that in many systems giant planets have distances to the parent star comparable with those of our terrestrial planets; sometimes even significantly smaller. It is believed that this is due to the general tendency that planets have to migrate towards the centre of the protoplanetary disc, due to gravitational interactions with the gas (see [8] for a review). Thus, a good model for the formation of the Solar System has to explain, first of all, why our giant planets did not migrate closer to the Sun.

It was argued in [9] that the observed pile-up of giant planets at 1–2 AU (astronomical units) from the central star is due to photo-evaporation opening a gap at approximately 1 AU in the protoplanetary disc. Although probably effective, this process is unlikely to explain a ‘distant’ planet like Jupiter; thus an alternative explanation is needed for the Solar System.

An important clue comes from the pioneering work in Masset & Snellgrove [10]. They did the first hydrodynamical simulation of the contemporary evolution of Jupiter and Saturn in a disc of gas. They realized that, when the two planets are on orbits with a large mutual separation, they both migrate towards the Sun, Saturn migrating faster than Jupiter. However, when the orbit of the latter approaches that of the former, Jupiter migration reverses. The two planets approach each other until they are locked in their mutual 2 : 3 mean motion resonance. Then, they migrate outwards together, preserving the resonant relationship between their orbital periods.

Both Morbidelli & Crida [11] and D'Angelo & Marzari [12] explored this phenomenon further, exploring the (somewhat restrictive) range of disc parameters that promote outward migration. Moreover, they showed that, as already conjectured in the study of Masset & Snellgrove [10], this process of outward migration is possible only if the mass of the outer planet is smaller than that of the inner one (mass ratios between one-fourth and one-half being 'ideal', which nicely encompasses the real Saturn/Jupiter mass ratio of one-third). To date, this is the only explanation for the distant orbit of Jupiter. If true, it also explains why the characteristic absence of giant planets in the inner Solar System is not a generic property of planetary systems. Systems with only one giant planet, or with multiple giant planets but with reversed mass ratio (the outer being the more massive), or with a too large temporal gap between the formation of the planets (precluding them from approaching sufficiently close to each other to trigger outward motion), would not avoid inward giant planet migration and, in the end, would have giant planets at approximately 1–2 AU or less from the central star.

The reversal of Jupiter and Saturn migration has been reproduced by numerous teams with independent hydrodynamical codes (see for instance [12,13]). From the point of view of terrestrial planet formation, the message of this result is that the expectation that the giant planets remained static on their current orbits while the Earth and its precursors formed is just naive.

This is important information to take into account. In fact, numerical models of terrestrial planet formation, starting from a disc of planetesimals and planetary embryos extending from the Sun to the current orbit of Jupiter, and assuming that the giant planets remain on fixed orbits, consistently failed to reproduce one characteristic of the real terrestrial planet system: the small mass of Mars [14,15].

It was convincingly shown in Hansen [16] that the key parameter to form a small Mars is the radial distribution of the solid material in the disc. If the outer edge of the disc of embryos and planetesimals is at about 1 AU, with no solid material outside this distance, the simulations achieve systematically a small Mars (together with a big Earth). The issue is then how to justify the existence of such an outer edge and how to explain its compatibility with the existence of the asteroid belt, between 2 and 4 AU. The asteroid belt has today a very small total mass (about 6×10^{-4} Earth masses [17]), but it is well known that it had to contain at least a thousand times more solid material when the asteroids formed [18].

The result in Hansen [16] motivated Walsh *et al*. [19] to combine terrestrial planet accretion with giant planet migration. The model in Walsh *et al*. [19] was built on the inward-then-outward migration scenario for Jupiter described above. The extent of the inward and outward migrations cannot be computed *a priori*, because they depend on properties of the disc and of giant planet accretion that are unknown, such as the time lag between Jupiter and Saturn formation, the speed of inward migration (depending on the disc's viscosity), the speed of outward migration (depending on the disc's scale height), the time lag between the capture in resonance of Jupiter and Saturn, and gas removal. However, the extent of the inward and outward migrations of Jupiter can be deduced by looking at the resulting structure of the inner Solar System. In particular, it was remarked in [19] that a reversal of Jupiter's migration at 1.5 AU would provide a natural explanation for the existence of the outer edge at 1 AU of the inner disc of embryos and planetesimals, required to produce a small Mars (figure 1). Because of the prominent inward-then-outward migration of Jupiter that it assumes, the scenario proposed in [19] is nicknamed 'Grand Tack'.

A crucial diagnostic of this scenario, though, is the survival of the asteroid belt. Given that Jupiter should have migrated through the asteroid belt region twice, first inwards, then outwards, one could expect that the asteroid belt should now be totally empty. However, the numerical simulations by Walsh *et al*. [19] show that the asteroid belt is first fully depleted by the passage of the giant planets, but then, while Jupiter leaves the region for the last time, it is repopulated by a small fraction of the planetesimals scattered by the giant planets during their migration. In particular, the inner asteroid belt is dominantly repopulated by planetesimals that were originally inside the orbit on which Jupiter formed, while the outer part of the asteroid belt is dominantly repopulated by planetesimals originally in between and beyond the orbits of the

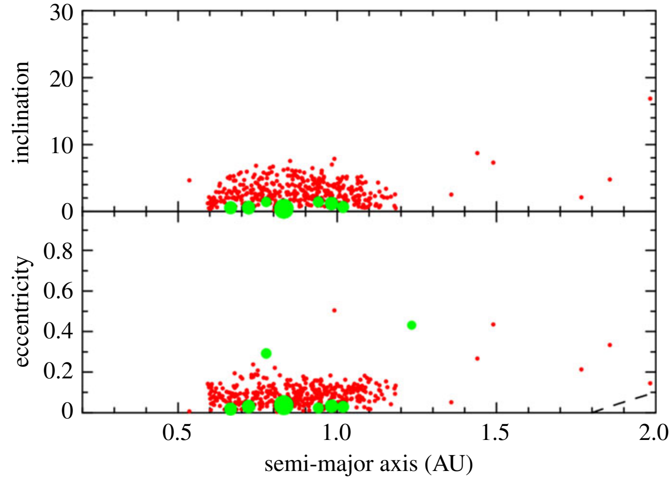

Figure 1. The orbits of embryos (larger, grey, circles; green online) and planetesimals (small, black, dots; red online) at the end of the inward-then-outward migration of Jupiter, as modelled in the 'Grand Tack', when the gas is fully removed. The dashed curve in the bottom right corner marks the inner boundary of the asteroid belt. From this state, the system evolves naturally in a time scale of a few 10^7 years into two Earth-mass planets at approximately 0.7 and 1 AU and a small Mars at 1.5 AU (figure 2). (Online version in colour.)

giant planets. Assuming that Jupiter accreted at the location of the snow line, it is then tempting to identify the planetesimals originally closer to the Sun with the anhydrous asteroids of E- and S-type, and those originally in between and beyond the orbits of the giant planets with the 'primitive' C-type asteroids. With this assumption, the Grand Tack scenario explains the physical structure of the asteroid belt (see above) probably better than any other previous model. In fact, it is difficult to explain the differences between ordinary/enstatite chondrite and carbonaceous chondrite parent bodies if they had both formed in the asteroid belt region, given that they are coeval [20] and that the radial extent of the asteroid belt is small (approx. 1 AU only). Instead, if ordinary/enstatite and carbonaceous chondrite parent bodies have been implanted into the asteroid belt from originally well-separated reservoirs, the differences in physical properties are easier to understand in the framework of the classical condensation sequence. The origin of C-type asteroids from the giant planet region would also explain, in a natural way, the similarities with comets that are emerging from recent observational results and sample analyses. The small mass of the asteroid belt, its eccentricity and inclination distribution are also well reproduced by the Grand Tack scenario.

All these results on the asteroid belt, together with the fact that the mass distribution of the terrestrial planets is also statistically reproduced (figure 2), make the Grand Tack scenario an appealing comprehensive model of terrestrial planet formation.

3. Extrasolar giant planet systems and the formation of Earth-like planets

I now try to speculate about the likelihood of habitable terrestrial planets (or more generally about the possible structures of terrestrial planet systems), on the basis of our understanding of the formation of terrestrial planets in our Solar System.

As repeatedly said above, a key and non-generic characteristic of our Solar System is that the giant planets are all at large distances and presumably never penetrated inside 1.5 AU from the Sun. The second important characteristic is that the orbits of the giant planets of the Solar System are quasi-circular, unlike those of most extrasolar giant planets known to date. Thus, below I consider four broad cases.

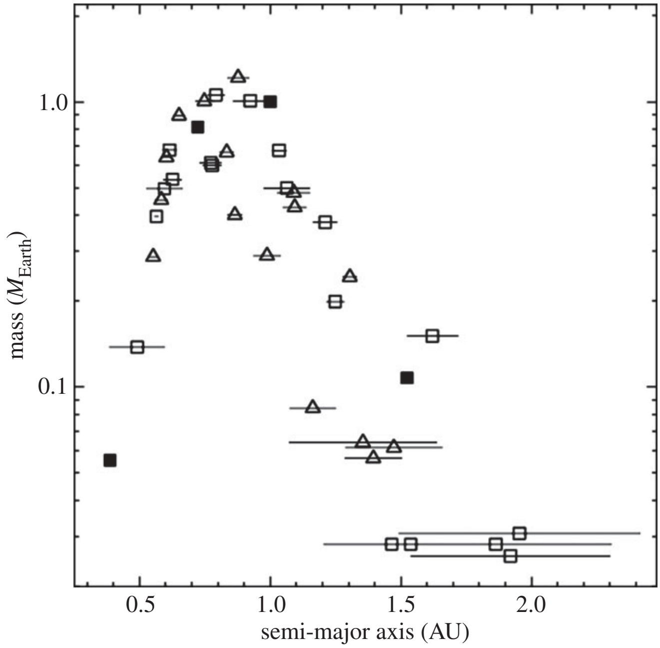

Figure 2. The mass distribution of the synthetic terrestrial planets produced in the Walsh *et al*. [19] simulations. The open symbols represent the planets produced in different runs starting from different initial conditions. The horizontal lines denote the perihelion–aphelion excursion of the planets on their eccentric final orbits. The filled black squares show the real planets of the Solar System. The large mass ratio between the Earth and Mars is statistically reproduced.

(a) Cases with giant planet systems similar to our own

If the giant planets remain in the outer part of the system on quasi-circular orbits, the accretion in the inner part of the disc proceeds along a well-studied path. Planetesimals first give rise to a system of more massive objects, known as planetary embryos, through the subsequent processes of runaway [21] and oligarchic [22] growth. These bodies have masses of the order of the mass of the Moon or Mars, depending on the initial surface density of solid material in the disc. Then, on the disappearance of the gas, the system of embryos develops a dynamical instability, which leads the embryos to acquire more eccentric orbits, so that they cross each other and collide on time scales of several millions of years [14]. This process of mutual giant impacts eventually leads to a few planets with masses comparable to that of the Earth [15]. The delivery of water-rich material from the vicinity of the giant planets seems to be quite a generic process [23–26]. The exact migration behaviour of the giant planets in the outer system should not play a crucial role, as long as their orbital eccentricities remain small. After all, from the point of view of Earth accretion (but not from the point of view of Mars!), the growth history is not qualitatively different in the Grand Tack scenario from that in the previous models assuming giant planets on fixed orbits. The habitable region is narrow, so not all terrestrial planet systems will have a habitable planet. However, among all the terrestrial planet systems formed, habitable planets should not be rare.

(b) Cases with giant planets that migrated into/through the habitable region due to planet–disc interactions

The migration of a giant planet into the habitable region has quite dramatic effects. It disrupts the planetesimal disc through which the giant planet migrates. This happens because of two mechanisms. The first one is capture in mean motion resonances with the migrating planet. Captured planetesimals are then forced to migrate together with the resonances. This can drag a

significant fraction of the material out of the habitable zone towards the star. These planetesimals are expected to accrete with each other and form terrestrial planets in these resonances, but they would inevitably be too close to the star to be habitable [27,28]. Curiously, the *Kepler* survey suggests the lack of terrestrial-like planets in the vicinity of hot Jupiters [29], as if this mechanism were not operational in reality.

The second mechanism for the disruption of the planetesimal disc is scattering. If the giant planets remain in/near the habitable region, they should prevent—by stirring and depleting their neighbourhood—the accretion of terrestrial planets in the same zone. This is similar to Jupiter stirring and depleting the asteroid belt, preventing the accretion of another planet there. However, if the giant planet migrates through the habitable zone rapidly, and leaves it, approaching the star, it is possible that enough planetesimals, scattered behind the orbit of the planet, have orbits re-circularized by gas drag so that they can eventually generate terrestrial planets [28] in a process similar to that discussed above for case (a).

(c) Cases with giant planets that developed large orbital eccentricities

Most extrasolar giant planets have large eccentric orbits. It is believed that they have been acquired during a phase of orbital instability and mutual scattering of the giant planet system [2,30]. For comparison, according to the *Nice model* describing the evolution of the Solar System after the dissipation of gas [31], the giant planets of our Solar System also underwent a similar instability, but the orbits of Jupiter and Saturn remained quasi-circular because the two major planets, by mere luck, avoided mutual encounters. Instead, Uranus and Neptune acquired large eccentric orbits, but eventually their eccentricities got damped by the dynamical friction exerted by the trans-Neptunian planetesimal disc.

The acquisition of large-eccentricity orbits by the most massive planets has devastating effects for the rest of the system. In fact, through a mechanism of secular perturbations, the eccentricities of all objects are forced to undergo large oscillations. This is true whatever the semi-major axes of the giant planet orbits, because secular perturbations are effective even at large distances. Simulations in Raymond *et al*. [32] show that a system of terrestrial planets immediately becomes destabilized when the giant planets jump onto eccentric orbits. Either all terrestrial planets are removed (they acquire orbits so eccentric as to collide with the central star or to intersect the trajectories of the giant planets, which then eject them onto hyperbolic orbits) or only one terrestrial planet survives, on an orbit so eccentric that it presumably prevents habitability.

Remember that most known extrasolar giant planets are close to their host star and have eccentric orbits. Thus, cases (b) and (c) seem to be the norm (not good for twin Earths), whereas case (a)—the Solar System case—seems to be the exception. However, owing to observational biases, we might not have found the giant planet systems that are most similar to our own.

(d) Cases with no giant planets

Only about 5–10% of solar-type stars harbour Jupiter-mass planets within a few astronomical units [4]. Thus, one might think that the remaining approximately 90% of the stars offer favourable conditions to form terrestrial planets, possibly habitable ones. In fact, it has been shown that, in the absence of giant planets, the formation of terrestrial planets on orbits with moderate eccentricities is a generic process [33]. However, things may not be so simple. Whereas the formation of Jupiter-mass planets may be relatively rare, the formation of massive objects, such as Uranus and Neptune, may be much more generic. Indeed, the overall analysis of all HARPS (High Accuracy Radial velocity Planet Searcher) candidates suggests a frequency of about 30% of exoplanets with mass smaller than 30 Earth masses orbiting solar-type stars with periods shorter than 100 days [4], denoted warm Neptunes hereafter.

There are two scenarios for the formation of these planets. One is that they accreted *in situ*, from a disc that accumulated a lot of solids in its inner part [34]. In this case, the formation of Neptune-mass planets on short-period orbits should not affect the formation of terrestrial planets

in the habitable zone. Whether Earth-like planets form in the habitable zone should depend only on the amount of solids that remain available in that part of the disc.

The second scenario, which explains better the low bulk densities observed for most of the warm Neptunes, is that they formed in the outer part of the disc, like giant planet cores, and then moved towards the star as a result of planet–disc interactions. In fact, when Neptune-mass planets are embedded in the disc of gas, they are expected to reside near a 'no-migration radius' resulting from the balance of the various torques that they suffer from the disc [35,36]. However, as the disc evolves and the amount of gas is reduced, the no-migration radius moves towards the star; thus, the giant cores eventually migrate towards the star until the gas is substantially removed [36]. This process seems to be generic and the only apparent reason for which Uranus and Neptune did not migrate down to 1 AU or so in our Solar System is that they have been retained in resonance by Jupiter and Saturn, which, as seen above, migrated outwards during the last phase of the lifetime of the disc. If this understanding of Solar System history is true, then one can speculate that in most systems without Jovian-mass planets the habitable zone is eventually 'invaded' by giant cores.

The effect of this invasion on a system of forming terrestrial planets has not been studied in detail, yet. One may expect that most of the solid materials originally in the habitable zone are captured in resonance with the migrating giant cores and are transported towards the star. In this process, rocky planets can form from the material shepherd in resonance with the giant cores, as already shown in Fogg & Nelson [27] for migrating giant planets, but they are eventually too close to the star to be habitable. The first evidence for this process may be the Kepler-36 system, made of a super-Earth just inside the orbit of a hot Neptune, with a large density ratio (the super-Earth is rocky, whereas the hot Neptune should be made of rock and ice with a substantial atmosphere of light gases like Neptune [37]). Thus, I expect that the invasion of giant cores into the habitable zone may be problematic for the formation of an Earth like ours. However, the giant cores themselves may turn out to be habitable, if they have the chance to end up in the appropriate zone, particularly if they are not very massive (less than a few Earth masses). I note that all the 'terrestrial planets' formed in the celebrated planetary synthesis models [38,39] are actually 'low-mass giant cores' (i.e. formed rapidly in a disc of gas and planetesimals) rather than planets like the Earth (formed on a time scale of several tens of million years, from mutual giant impacts among low-mass planetary embryos in a gas-free environment).

How often do cases (a)–(d) occur in planetary systems? Currently, nobody can answer this fundamental question. From the observational viewpoint, our census of extrasolar planetary systems is still too limited and biased. From the modelling point of view, one would need a good understanding of the process of formation of the giant cores and Jovian planets that currently does not exist.

4. Conclusion

Like the configuration of the giant planets of our Solar System is not typical of observed extra-solar systems, the same is probably true for the terrestrial planets. The properties of the terrestrial planets in our system are due to the fact that the giant planets did not migrate down to approximately 1 AU and they remained on quasi-circular orbits. The formation and evolution of the terrestrial planets would have been radically different if the giant planets had passed through the habitable zone or had acquired large orbital eccentricities, like in most of the planetary systems observed to date.

My conclusion is therefore that we should expect Earth-like planets to be rare, where by 'Earth-like' I mean planets that are not just similar to the Earth in their final characteristics, but also in their formation history. This does not imply, though, that habitable worlds are rare. It just implies that most other habitable worlds are *different*. Possibly, most frequent habitable worlds are Earth- or super-Earth-mass planets that are failed cores of giant planets (in the sense that they did not grow big enough and fast enough to accrete a substantial amount of gas) and which migrated into

the habitable zone. Most of these bodies would be rich in water, as they started to form beyond the snow line, so ultimately they could be ocean planets [40]. The moons of giant planets that migrated into the habitable zone could also be relatively frequent habitable worlds.

References

1. Rasio FA, Ford EB. 1996 Dynamical instabilities and the formation of extrasolar planetary systems. *Science* **274**, 954–956. (doi:10.1126/science.274.5289.954)
2. Juric M, Tremaine S. 2008 Dynamical origin of extrasolar planet eccentricity distribution. *Astrophys. J.* **686**, 603–620. (doi:10.1086/590047)
3. Raymond SN, Barnes R, Veras D, Armitage PJ, Gorelick N, Greenberg R. 2009 Planet–planet scattering leads to tightly packed planetary systems. *Astrophys. J.* **696**, L98–L101. (doi:10.1088/0004-637X/696/1/L98)
4. Mayor M *et al*. 2011 The HARPS search for southern extra-solar planets XXXIV. Occurrence, mass distribution and orbital properties of super-Earths and Neptune-mass planets. *Astron. Astrophys.* (http://arxiv.org/abs/1109.2497)
5. Levison HF, Thommes E, Duncan MJ. 2010 Modeling the formation of giant planet cores. I. Evaluating key processes. *Astron. J.* **139**, 1297–1314. (doi:10.1088/0004-6256/139/4/1297)
6. Haisch Jr KE, Lada EA, Lada CJ. 2001 Disk frequencies and lifetimes in young clusters. *Astrophys. J.* **553**, L153–L156. (doi:10.1086/320685)
7. Kleine T, Touboul M, Bourdon B, Nimmo F, Mezger K, Palme H, Jacobsen SB, Yin QZ, Halliday AN. 2009 Hf–W chronology of the accretion and early evolution of asteroids and terrestrial planets. *Geochim. Cosmochim. Acta* **73**, 5150–5188. (doi:10.1016/j.gca.2008.11.047)
8. Kley W, Nelson RP. 2012 Planet–disk interaction and orbital evolution. *Annu. Rev. Astron. Astrophys.* **50**, 211–249. (doi:10.1146/annurev-astro-081811-125523)
9. Alexander RD, Pascucci I. 2012 Deserts and pile-ups in the distribution of exoplanets due to photoevaporative disc clearing. *Mon. Not. R. Astron. Soc.* **422**, L82–L86. (doi:10.1111/j.1745-3933.2012.01243.x)
10. Masset F, Snellgrove M. 2001 Reversing type II migration: resonance trapping of a lighter giant protoplanet. *Mon. Not. R. Astron. Soc.* **320**, L55–L59. (doi:10.1046/j.1365-8711.2001.04159.x)
11. Morbidelli A, Crida A. 2007 The dynamics of Jupiter and Saturn in the gaseous protoplanetary disk. *Icarus* **191**, 158–171. (doi:10.1016/j.icarus.2007.04.001)
12. D'Angelo G, Marzari F. 2012 Outward migration of Jupiter and Saturn in evolved gaseous disks. *Astrophys. J.* **757**, 50. (doi:10.1088/0004-637X/757/1/50)
13. Pierens A, Nelson RP. 2008 On the formation and migration of giant planets in circumbinary discs. *Astron. Astrophys.* **483**, 633–642. (doi:10.1051/0004-6361:200809453)
14. Chambers JE. 2001 Making more terrestrial planets. *Icarus* **152**, 205–224. (doi:10.1006/icar.2001.6639)
15. Raymond SN, O'Brien DP, Morbidelli A, Kaib NA. 2009 Building the terrestrial planets: constrained accretion in the inner Solar System. *Icarus* **203**, 644–662. (doi:10.1016/j.icarus.2009.05.016)
16. Hansen BMS. 2009 Formation of the terrestrial planets from a narrow annulus. *Astrophys. J.* **703**, 1131–1140. (doi:10.1088/0004-637X/703/1/1131)
17. Krasinsky GA, Pitjeva EV, Vasilyev MV, Yagudina EI. 2002 Hidden mass in the asteroid belt. *Icarus* **158**, 98–105. (doi:10.1006/icar.2002.6837)
18. Wetherill GW. 1989 Origin of the asteroid belt. *Asteroids* **II**, 661–680.
19. Walsh KJ, Morbidelli A, Raymond SN, O'Brien DP, Mandell AM. 2011 Sculpting of the inner Solar System by gas-driven orbital migration of Jupiter. *Nature* **475**, 206–209. (doi:10.1038/nature10201)
20. Villeneuve J, Chaussidon M, Libourel G. 2009 Homogeneous distribution of ^{26}Al in the Solar System from the Mg isotopic composition of chondrules. *Science* **325**, 985–988. (doi:10.1126/science.1173907)
21. Greenberg R, Hartmann WK, Chapman CR, Wacker JF. 1978 Planetesimals to planets—numerical simulation of collisional evolution. *Icarus* **35**, 1–26. (doi:10.1016/0019-1035(78)90057-X)
22. Kokubo E, Ida S. 1998 Oligarchic growth of protoplanets. *Icarus* **131**, 171–178. (doi:10.1006/icar.1997.5840)

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23. Morbidelli A, Chambers J, Lunine JI, Petit JM, Robert F, Valsecchi GB, Cyr KE. 2000 Source regions and time scales for the delivery of water to Earth. *Meteorit. Planet. Sci.* **35**, 1309–1320. (doi:10.1111/j.1945-5100.2000.tb01518.x)
24. Raymond SN, Quinn T, Lunine JI. 2004 Making other Earths: dynamical simulations of terrestrial planet formation and water delivery. *Icarus* **168**, 1–17. (doi:10.1016/j.icarus.2003.11.019)
25. Raymond SN. 2006 The search for other Earths: limits on the giant planet orbits that allow habitable terrestrial planets to form. *Astrophys. J.* **643**, L131–L134. (doi:10.1086/505596)
26. O'Brien DP, Morbidelli A, Levison HF. 2006 Terrestrial planet formation with strong dynamical friction. *Icarus* **184**, 39–58. (doi:10.1016/j.icarus.2006.04.005)
27. Fogg MJ, Nelson RP. 2005 Oligarchic and giant impact growth of terrestrial planets in the presence of gas giant planet migration. *Astron. Astrophys.* **441**, 791–806. (doi:10.1051/0004-6361:20053453)
28. Raymond SN, Mandell AM, Sigurdsson S. 2006 Exotic Earths: forming habitable worlds with giant planet migration. *Science* **313**, 1413–1416. (doi:10.1126/science.1130461)
29. Steffen JH *et al*. 2012 *Kepler* constraints on planets near hot Jupiters. *Proc. Natl Acad. Sci. USA* **109**, 7982–7987. (doi:10.1073/pnas.1120970109)
30. Moorhead AV, Adams FC. 2005 Giant planet migration through the action of disk torques and planet scattering. *Icarus* **178**, 517–539. (doi:10.1016/j.icarus.2005.05.005)
31. Morbidelli A, Tsiganis K, Crida A, Levison HF, Gomes R. 2007 Dynamics of the giant planets of the solar system in the gaseous protoplanetary disk and their relationship to the current orbital architecture. *Astron. J.* **134**, 1790–1798. (doi:10.1086/521705)
32. Raymond SN, Armitage PJ, Moro-Martin A, Booth M, Wyatt MC, Armstrong JC, Mandell AM, Selsis F, West AA. 2011 Debris disks as signposts of terrestrial planet formation. *Astron. Astrophys.* **530**, A62. (doi:10.1051/0004-6361/201116456)
33. Levison HF, Agnor C. 2003 The role of giant planets in terrestrial planet formation. *Astron. J.* **125**, 2692–2713. (doi:10.1086/374625)
34. Hansen BMS, Murray N. 2012 Migration then assembly: formation of Neptune-mass planets inside 1 AU. *Astrophys. J.* **751**, 158. (doi:10.1088/0004-637X/751/2/158)
35. Paardekooper S-J, Mellema G. 2006 Halting type I planet migration in non-isothermal disks. *Astron. Astrophys.* **459**, L17–L20. (doi:10.1051/0004-6361:20066304)
36. Lyra W, Paardekooper S-J, Mac Low M-M. 2010 Orbital migration of low-mass planets in evolutionary radiative models: avoiding catastrophic infall. *Astrophys. J. Lett.* **715**, L68–L73. (doi:10.1088/2041-8205/715/2/L68)
37. Carter JA *et al*. 2012 Kepler-36: a pair of planets with neighboring orbits and dissimilar densities. *Science* **337**, 556–559. (doi:10.1126/science.1223269)
38. Ida S, Lin DNC. 2004 Toward a deterministic model of planetary formation. II. The formation and retention of gas giant planets around stars with a range of metallicities. *Astrophys. J.* **616**, 567–572. (doi:10.1086/424830)
39. Mordasini C, Alibert Y, Benz W, Klahr H, Henning T. 2012 Extrasolar planet population synthesis. IV. Correlations with disk metallicity, mass, and lifetime. *Astron. Astrophys.* **541**, A97. (doi:10.1051/0004-6361/201117350)
40. Leger A *et al*. 2004 A new family of planets? 'Ocean-planets'. *Icarus* **169**, 499–504. (doi:10.1016/j.icarus.2004.01.001)