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On the possibility of terrestrial planet formation in hot-Jupiter systems

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Abstract: About a fifth of the exoplanetary systems that have been discovered contain a so-called hot-Jupiter – a giant planet orbiting within 0.1 AU of the central star. Since these stars are typically of the F/G spectral type, the orbits of any terrestrial planets in their habitable zones at ∼1 AU should be dynamically stable. However, because hot-Jupiters are thought to have formed in the outer regions of a protoplanetary disc, and to have then migrated through the terrestrial planet zone to their final location, it is uncertain whether terrestrial planets can actually grow and be retained in these systems. In this paper we review attempts to answer this question. Initial speculations, based on the assumption that migrating giant planets will clear planet-forming material from their swept zone, all concluded that hot-Jupiter systems should lack terrestrial planets. We show that this assumption may be incorrect, for when terrestrial planet formation and giant planet migration are simulated simultaneously, abundant solid material is predicted to remain from which terrestrial planet growth can resume.

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Introduction

One of the recent triumphs of astronomy has been the discovery of numerous exoplanetary systems, containing one or more detected giant planet (Fischer *et al.* 2004; Marcy *et al.* 2005). About 5% of F/G main sequence stars have so far been shown to have planets, a proportion that can only rise as techniques improve, and it is now possible to argue that Jupiter-like planets are not uncommon, at least around Sun-like stars (Lineweaver & Grether 2003). However, these systems have been found to exhibit a great variety of orbital arrangements, with giant planets being located in a wide range of semi-major axes and eccentricities. Few examples to date have been found that are similar to the near-circular Sun–Jupiter–Saturn configuration of the Solar System.

The subset of exoplanetary systems that exhibit the most extreme rearrangement of planetary mass when compared to the Solar System are those containing so-called 'hot-Jupiters' – giant planets found within 0.1 AU of their central star in tidally circularized orbits. The first exoplanet to be discovered around a main sequence star, 51 Pegasi b, was of this type (Mayor & Queloz 1995) and since then they have accounted for ∼20% of the total exoplanet discoveries, where ∼1% of those discoveries have been F/G class stars. Since hot-Jupiters are the easiest kind of exoplanet to detect via the radial-velocity method, and are thus well sampled, these abundance estimates may be more widely applicable, implying the existence of $\sim 10^8$ such systems in the galaxy. The probability of a star hosting a hot-Jupiter has been found to increase with the star's heavy element content and typically stars with hot-Jupiters have a higher metallicity than the Sun. Exoplanetary systems in general also show this correlation (Santos *et al.* 2003; Fischer & Valenti 2005), suggesting giant planets may form more efficiently in protoplanetary discs where solid matter is abundant.

It is unlikely that hot-Jupiters originally formed at their present locations because of the restricted gravitational reach of a protoplanet and the high ambient temperatures so close to the central star (Bodenheimer *et al.* 2000). Giant planets are more likely to form in the cooler regions of a disc beyond the nebula snowline (e.g. Pollack *et al.* 1996). Mutual scattering of giant planets formed in this outer region could result in the periastron of one of them being delivered close to the central star whereupon tidal forces could circularize the orbit and draw down its semi-major axis, but this mechanism experiences difficulties in explaining the closest orbits and their relative abundance (Marzari & Weidenschilling 2002; Adams & Laughlin 2003). The leading hypothesis explaining the origin of hot-Jupiters is planetary migration, driven by a tidal interaction between a planet and the protoplanetary disc in which it is embedded (Lin & Papaloizou 1986; Ward 1997). Calculations have shown that the planet will generate density waves in the nebular gas at Lindblad resonance positions, clearing an annular gap in a zone where the planetary torques dominate the intrinsic viscous torques of the disc. These density waves exert a back-reaction torque on the planet and usually the outer disc torques dominate those of the inner disc resulting in an inwards migration of the planet. This situation arises for planets more massive than $\sim$100 $m_{\oplus}$ and is referred to as a type II migration: the giant planet is locked into the viscous evolution of the disc and drifts inwards over a disc viscous timescale. Typically, giant planets are predicted to migrate from their formation location at several AU to a position close to the central star in $\sim 10^5$ years (e.g. Nelson *et al.* 2000). The mechanism that actually halts the migration, allowing the planet to survive, is presently unknown but a number of proposals have been aired, such as the planet moving into a central magnetospheric cavity in the gas, Roche lobe overflow to and tidal interactions with a rapidly rotating protostar and fortuitous disc dispersal. It is possible that some migrating planets do not survive and eventually merge with the central star (Trilling *et al.* 1998; Armitage *et al.* 2002).

Prediction of the presence of terrestrial planets in exoplanetary systems is complicated by the fact that the orbits of the most massive planets constrain both the formation and long-term survival of smaller bodies and so models that explain the formation of the Solar System terrestrial planets may only be of partial relevance. Moreover, the presence of a hot-Jupiter implies that it must have traversed the region where rocky planets are expected to form, including through the system's habitable zone (HZ) where planets with an Earth-like climate are possible (Kasting *et al.* 1993). This must have happened early on, whilst the nebular gas was still present and before the completion of terrestrial planet growth. As a minimum, we might sensibly conjecture that such a potentially disruptive event would have significant consequences for the growth and survival of the inner system planets. However, it has become customary to assume that interior planetary formation is prevented completely by the passage of the giant planet and that the entire swept zone is cleared of material, thus rendering hot-Jupiter systems barren. This assumption is one of those at the heart of two well-known astrobiological hypotheses, the Rare Earth Hypothesis (Ward & Brownlee 2000) and the Galactic Habitable Zone (Lineweaver 2001; Lineweaver *et al.* 2004), that draw on current knowledge and opinion in an attempt to place constraints on the occurrence of life elsewhere in the galaxy. The Rare Earth Hypothesis proposes that, whilst microbial life might originate and thrive in a variety of extraterrestrial settings, complex multicellular life requires such a restricted set of environmental conditions it is likely to be very rare or non-existent elsewhere in the universe. From this point of view, any significant deviation in planetary parameters away from those exemplified by the Earth's ideal reduces or negates prospects for complex life. Similarly, any deviation in planetary system architecture from that exemplified by the Solar System will impair the habitability of any Earth-like planets formed there. Star systems containing hot-Jupiters therefore are an obvious target for pruning from the list of potentially habitable locations. The concept of the Galactic Habitable Zone also assumes hot-Jupiter systems to be hostile to biology. This assumption, together with the observation that hot-Jupiter host stars are typically more metal-rich than the Sun, is then used to propose that the metal-rich inner regions of the entire galaxy are devoid of Earth-like planets.

How realistic is the conjecture that hot-Jupiter systems inevitably lack terrestrial planets? If the planet-forming material of the interior disc traversed by the giant is removed, how does this happen and where does it go? Is all this matter accreted by the central star or the giant, or does some fraction survive in sufficient quantity for renewed planetary growth after the giant has migrated to its final position? If the solids disc does survive, should we actually expect the presence of terrestrial planets in these systems?

In this paper we briefly review recent progress in clarifying this issue, including studies of the dynamical habitability of hot-Jupiter systems, and the modelling of terrestrial planet formation in the presence of a migrating giant planet. Whilst no consensus has yet emerged, and work is preliminary and ongoing, some opinion is beginning to cast doubt on the Rare Earth viewpoint.

Dynamical habitability

The question of whether terrestrial planets can form in the HZ of a given exoplanetary system only becomes relevant to astrobiology if planetary orbits there can remain stable over the long term. A number of studies have looked at this issue of dynamical habitability by using numerical integration to calculate the orbital evolution of fictitious terrestrial planets inserted into the HZs of exoplanetary systems simulated on a computer (e.g. Jones *et al.* 2001).

The most useful to our discussion here are those that have addressed the entire set of systems known at the time, including those containing close-orbiting giant planets. There have been two distinct approaches:

(1) short-term (1 Myr) integrations looking at the survival statistics in all the known systems of a large number of massless test particles scattered within the HZ (Menou & Tabachnik 2003);
(2) long-term (1000 Myr) integrations of Earth-mass planets in the HZs of a limited, but representative, set of systems and evaluation of the habitability of other systems by extrapolation from this data set (Jones *et al.* 2005).

Although these studies differ in the detail of some of their assumptions – such as the width and age of the HZ, the simulated mass of the giant and their criteria as to what constitutes a habitable orbit – their conclusions are comparable. Both approaches conclude that $\sim$50% of exoplanetary systems are unlikely to contain a habitable planet because the dominant giant planet in these systems orbits too close to or even through the HZ. The other 50% of systems permit some degree of survival. Menou & Tabachnik (2003) estimate that the HZs of $\sim$25% of exoplanetary systems are as dynamically stable as the Solar System with the other 25% exhibiting stable orbits in more restricted regions of the HZ. Jones *et al.* (2005), who include a stellar evolution model and an evolving HZ in their calculations, conclude that 49% of exoplanetary systems could have had an Earth-mass planet confined to some or all of the HZ for at least the past 1000 Myr up to the present day.

An important detail to be gained from this work is that the HZs of hot-Jupiter systems, and other exoplanetary systems with close-orbiting giants at distances of less than 0.4 AU, exhibit good dynamical stability throughout their full width. The proximity of these giant planets to the central star and their low eccentricities precludes a significant disturbance of planetary orbits in the ~1 AU region. If habitable planets exist in these systems, then their orbits should stay put for billions of years. As Jones *et al.* (2005) have pointed out, this finding emphasizes the need to answer the unsolved question of whether habitable planets can actually form in hot-Jupiter systems, for if we accept the Rare Earth assumption that giant planet migration permanently clears the traversed zone of smaller planets, then their estimated fraction of exoplanetary systems that might host a habitable planet falls from 49 % to 7 %. The effect of eliminating hot-Jupiter systems from the habitable planet equation is so drastic because most of the exoplanetary systems we know of which have dynamically stable HZs contain a close-orbiting giant planet.

Planet formation in hot-Jupiter systems: preliminary studies

The first paper to pay attention to some of the issues involved in terrestrial planet formation in hot-Jupiter systems was that of Armitage (2003). However, his work does not address any of the questions involving the actual effect of giant planet migration on an interior planet-forming disc. Instead, it assumes this disc is removed and uses a time-dependent model of a protoplanetary disc to calculate the subsequent evolution of both gas and dust in order to ascertain whether the evacuated interior can be replenished with sufficient solid matter from the outer disc to provide for a second generation of planetesimals and renewed planet formation. His conclusions were that, for reasonable disc parameters and lifetimes, replenishment will be inefficient such that planetesimal surface densities would be reduced by 1–2 orders of magnitude at 1 AU following giant planet migration. For sufficient time to elapse for good replenishment to occur, Armitage found that the migration episode must occur at a very early stage –within the first ~0.1–1.0 Myr of a disc where the gas component lasts for ~8 Myr. Since it appears improbable that gas giant planet core formation, envelope growth and migration could all be squeezed into the first ~1–10 % of the gas disc lifetime, Armitage concludes that no substantial terrestrial planets will be found in hot-Jupiter systems in orbits interior to the original formation position of the giant planet.

A completely different approach to the problem was taken by Mandell & Sigurdsson (2003) who consider a late migration scenario and use *N*-body simulations to model the migration of a Jupiter-mass planet through a fully formed terrestrial planet system. Specifically, they take the example of the present day Solar System and consider what would happen if Jupiter migrated inward to 0.1 AU over three different timescales of 0.5, 1.0 and 2.0 Myr. The typical pattern of events observed included:

(1) the capture of planetary orbits into sweeping resonances with the inward migrating giant, resulting in orbital shrinkage and excitation;
(2) close encounters between the planets resulting in collisions or mutual scattering;
(3) slingshot encounters with the giant as it passed through the inner system, leading to ejection, collision with the central star or scattering into eccentric but bound exterior orbits.

Overall ~25 % of the planets survived in a wide variety of orbits exterior to the giant, the survival probability being highest for the shortest migration times. Some of these orbits, they speculated, might subsequently become circularized as a result of dynamical friction[1] with outer system planetesimals or interaction with a remnant gas disc (e.g. Agnor & Ward 2002; Kominami & Ida 2002). Their conclusion therefore was that inward migration of a giant planet does *not* always remove pre-formed terrestrial planets and that, given an initial arrangement of bodies similar to that of the Solar System, between around 1 % and 4 % of systems in which migration occurred could still possess a planet in the HZ.

Formation of terrestrial planets in the presence of a hot-Jupiter has been modelled by Raymond *et al.* (2005). They do not model the preceding migration of the giant planet and the disc material it passes through is assumed to be lost. Thus, in order to provide the material for terrestrial planet formation, they propose that the migration episode happens rapidly and early on, giving enough time for an exterior planetesimal disc to regenerate in the manner described by Armitage (2003). Their simulations therefore begin with the hot-Jupiter placed in its final close orbit and they proceed to model the later stages of terrestrial planet accretion from an exterior protoplanet disc using *N*-body methods. Their conclusion is that the presence of a hot-Jupiter does little to interfere with terrestrial planet formation outside of an annulus that is within a factor of three in period to the giant (about a factor of two in semi-major axis). Planet formation in the HZ, and water delivery to these planets which they also model, is not adversely affected, spurring the authors to suggest that stars with hot-Jupiters might actually be good places to search for habitable planets.

The conclusions of these three papers are divergent in that they bracket the widest possible range of outcomes, from the occurrence of terrestrial planets in hot-Jupiter systems being highly unlikely, through possible but rare, to commonplace. This confusion originates from the fact that all three models are different, adopt uncertain initial conditions and are not modelling the same aspect of the problem. The central question of what happens to the original protoplanetary disc traversed by the giant is not addressed, and both Armitage (2003) and Raymond *et al.* (2005) assume a total loss of planetary building blocks from the swept zone. Whilst

[1] A drag caused by numerous gravitational encounters with smaller bodies that has the effect of damping orbital eccentricity.

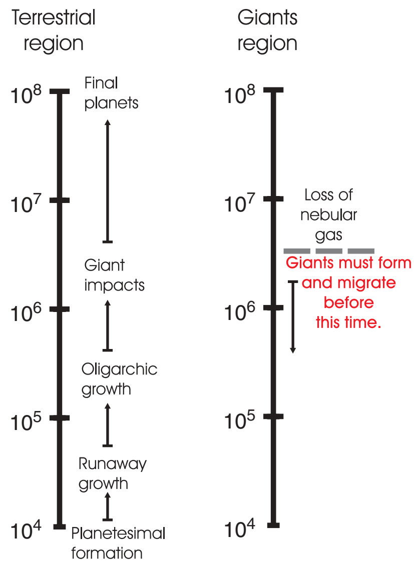

Fig. 1. Comparison of relevant simultaneous events in the terrestrial and giant planet formation regions. The vertical axes are timescales, measured in years.

Armitage (2003) then determines from this that future terrestrial planet formation is improbable, Raymond *et al.* (2005) propose the opposite by adopting an early migration scenario that gives time for a terrestrial planet forming disc to regenerate. The work of Mandell & Sigurdsson (2003) showing that planet-sized bodies can survive a giant planet migration episode suggests that the assumption of total inner disc loss is unrealistic and that some significant surviving remnant should be taken into account. However, the timing implicit in their scenario of a giant migrating through a mature terrestrial planetary system may be problematic, as giant planet migration is constrained to occur within the ~1–10 Myr lifetime of the gas disc whereas the terminal 'giant impacts' phase of terrestrial planet formation is thought to last ~100 Myr (e.g. Chambers 2001). The accretion of an inner planetary system is therefore likely to be incomplete at the time of any migration epoch with its population consisting of a large number of protoplanets and planetesimals, rather than four full-sized planets.

The time at which giant planet migration occurs is therefore of critical importance in the study of this problem as it entangles initially isolated sequences of events inside and beyond the nebula snowline (see Fig. 1). Since the gas component of a protoplanetary disc is comparatively short-lived (Greaves 2005), the one fairly certain constraint we have, which gives an upper limit to the time available, is that giant planets must both form and migrate in considerably less than 10 Myr. Observations suggest that 50% of young stars in clusters have lost their gas discs by an age of ~3 Myr and that overall gas disc lifetimes are ~4–8 Myr (Haisch *et al.* 2001). Estimation of a lower age limit is more problematic as it must rely on our incomplete theories of giant planet formation. The recently revived gravitational instability model, where giant planets form via the direct collapse of fragments of the protoplanetary disc, predicts that giant gaseous protoplanets can form in just ~1000 years and contract down to planetary densities in as little as ~0.1 Myr (Boss 2002; Mayer *et al.* 2002). However, the more favoured core-accretion model requires a much longer period to form giant planets as a ~10 $m_{\oplus}$ solid core must be accreted first, followed by the accumulation of a massive gas envelope. Early core accretion models suggested that Jupiter would have taken 1–10 Myr to form in this way, a time period close to or in excess of the dispersal timescale of the nebular gas (Pollack *et al.* 1996). However, more recent core accretion models have lowered this estimate to ~1 Myr (Alibert *et al.* 2004, 2005a; Papaloizou & Nelson 2005, Hubickyj *et al.* 2005) and better account for other observational constraints (Alibert *et al.* 2005b). Moreover, only the core accretion model can account for the correlation of exoplanet frequency and stellar metallicity, with its implication that giant planet formation is dependent on the solids content of the protoplanetary disc. Thus, it might be that the most realistic time period in which we might expect a giant planet migration episode would be in a protoplanetary disc that is ~0.5–3 Myr old, mature enough to have formed a giant planet but not so old that the gas has been lost.

In the meantime, accretion will be ongoing within the planetesimal swarm in the terrestrial planet region (see Fig. 1). According to the current picture, an early phase of runaway growth will give way to a lengthier period of oligarchic growth where similar sized protoplanets emerge from the swarm in well-spaced orbits which remain near circular due to dynamical friction from the surrounding sea of planetesimals (Kokubo & Ida 1998). Oligarchic growth ends when the mass remaining in planetesimals declines to the extent that their damping effect on protoplanet orbits becomes insufficient to prevent orbit crossing. This inaugurates the last phase of terrestrial planet formation; that of so-called 'giant impacts', involving the mutual accretion of protoplanets and the thinning down of their number to the point where the final planets emerge, positioned in stable non-crossing orbits. Simulations of this final stage of terrestrial planet growth suggest that it would take ~100 Myr to complete (e.g. Chambers 2001), long after the disappearance of the nebular gas. However, oligarchic growth starts much earlier, whilst gas is still present: simulations by Kokubo & Ida (2000) have shown that it takes only ~0.5 Myr to generate near Lunar-mass planetary embryos from a planetesimal disc at 1 AU. Thus, in the case of a giant planet migrating through the terrestrial planet zone, it seems most probable that this would occur at some time within, or towards the end of, the phase of oligarchic growth in that region. By the time a giant planet has grown large enough to start type II migration, considerable accretion into large planetary embryos could have already occurred in the inner system, bodies which might not be so readily swept up or dumped onto the central star. Far from it being clear that all this inner disc material is lost, hypotheses or models that assume this may be oversimplifying the problem, affecting any conclusions they make. Modelling giant planet migration *simultaneously* with terrestrial planet accretion is a clear pre-requisite for a realistic appraisal of this problem.

Planet formation in the presence of a migrating giant planet

The first study to model inner system planetary accretion in the presence of a migrating giant planet was that of Fogg & Nelson (2005). Their model, in the form of an *N*-body simulation, using the Mercury 6 integrator (Chambers 1999) with added gas drag and type II migration forces, consisted of a protoplanet/planetesimal disc extending from 0.4 to 4.0 AU, generated in line with the Minimum Mass Solar Nebula (MMSN) model[2] of Hayashi (1981) and the oligarchic growth picture of Kokubo & Ida (2000), but scaled up in mass by a factor of three ($3 \times$ MMSN)[3]. A nominal age of 0.5 Myr was adopted for this disc and to provide the basis of five migration scenarios through progressively evolved inner system material, five examples were allowed to accrete by being run for between 0.1 and 3.0 Myr. A 0.5 m_J giant planet was then introduced into the simulations at 5.0 AU and caused to migrate inwards at a rate prescribed by the local viscous disc evolution timescale (assuming a disc alpha viscosity of $\alpha = 2 \times 10^{-3}$). After an elapsed time of $\sim$170 000 years, the giant reached 0.1 AU, at which point the simulations were halted and the distribution of the remaining solid material analysed.

In all five of their scenarios, Fogg & Nelson (2005) found that the majority of the disc solids *survive* the passage of the giant planet, either by being shepherded inwards of the giant, or by being scattered by the giant into excited exterior orbits. This partition of solid material was shown to vary with the level of dissipative forces present (gas drag and dynamical friction), declining with disc maturity and favouring shepherding at early times and scattering at late times. Within the portion of the disc compacted inside the increasingly restricted volume interior to the giant, accretion was found to accelerate, often resulting in the formation of a massive terrestrial planet inside 0.1 AU. The fate of the material scattered into external orbits was not subjected to further calculation but it was noted that ample material remained to provide for the eventual accretion of a set of external terrestrial planets, including within the system's HZ. The need to invoke a secondary terrestrial planet-forming disc composed of material originating beyond 5 AU does not arise. Fogg & Nelson (2005) therefore concluded that the assumption that hot-Jupiter systems are devoid of inner system terrestrial planets is probably incorrect and that planet formation and the retention of planets both interior and exterior to a hot-Jupiter is possible.

One of the simplifications of the Fogg & Nelson (2005) model was its assumption of a steady state gas disc of fixed mass and surface density profile. More realistically, the nebula would be evolving under the influence of internal viscous forces and the tidal forces of embedded giant planets. The amount of gas present and its surface density profile would change with time as gas accretes onto the central star and annular gaps form in the neighbourhood of giant planet orbits. Compared to an undepleted gas disc, we might expect a reduction in the strength of dissipative forces present, especially in regions close to the central star and the giant. To improve the realism of this aspect of our model we have therefore added a one-dimensional time-dependent viscous gas disc model to our *N*-body code (see Lin & Papaloizou 1986) that allows the gas to deplete over time via accretion onto the central star, form an annular gap in the vicinity of the giant planet and self-consistently drive the giant planet inwards (Fogg & Nelson 2006). An example of one of these more recent runs is presented below.

The starting point of the example migration scenario is shown in Fig. 2, where the three panels show, for each object, their orbital eccentricity, inclination and mass, from top to bottom, respectively. The bottom panel also shows the gas surface density, read on the right-hand axis, for the initial $r^{-1.5}$ profile (the upper line) and the evolved profile (the lower line). We assume a nominal age for the protoplanetary disc of 0.5 Myr and the system shown in Fig. 2 has been arrived at by allowing it to evolve for 0.1 Myr before insertion of the giant planet at 5 AU. (Our model time, indicated in the figure, is initialized to $t = 0$ at the moment of introduction of the giant planet.) The solids disc consists of both protoplanets (the large coloured dots) and 'superplanetesimals' (the small black dots), particles that represent an idealized ensemble of a much larger number of real planetesimals. These two components behave differently: protoplanets interact gravitationally with all the bodies in the simulation and can grow via accretion, whereas superplanetesimals are non-self-interacting and can only be accreted. However, superplanetesimals experience gas drag, the force of which is evaluated as if for a 10 km radius planetesimal of realistic mass. (A full description of the model, its initial conditions and the generation of the solids disc are given in Fogg & Nelson 2005.) It can be seen in Fig. 2 that in this preceding 0.1 Myr, some dynamical spreading of the disc has occurred, as has some protoplanetary growth at the expense of the planetesimal population. (The initial masses of protoplanets were chosen as 0.025 $m_\oplus$ and 0.1 $m_\oplus$ interior and exterior, respectively, to the nebular snowline at 2.7 AU.) The gas surface density has also evolved away from its initial profile, falling most noticeably in the inner regions where it is accreting onto the central star. No dynamical or tidal effects of the giant planet on the gas and particles respectively are yet apparent as it has only just been inserted.

The state of the system at $t = 40\,000$ years is shown in Fig. 3. The giant planet has opened a gap in the gas and has migrated

[2] The MMSN model adopts an initial protoplanetary disc mass profile that can account for the formation of the terrestrial planets and the cores of the giant planets with a minimal transfer of material in the radial direction.

[3] The reason for this mass increase is that all giant planet formation theories demand it (e.g. Lissauer 1987; Pollack *et al.* 1996; Boss 2002; Thommes *et al.* 2003). Our choice of $3 \times$ MMSN is toward the lower end of estimated requirements.

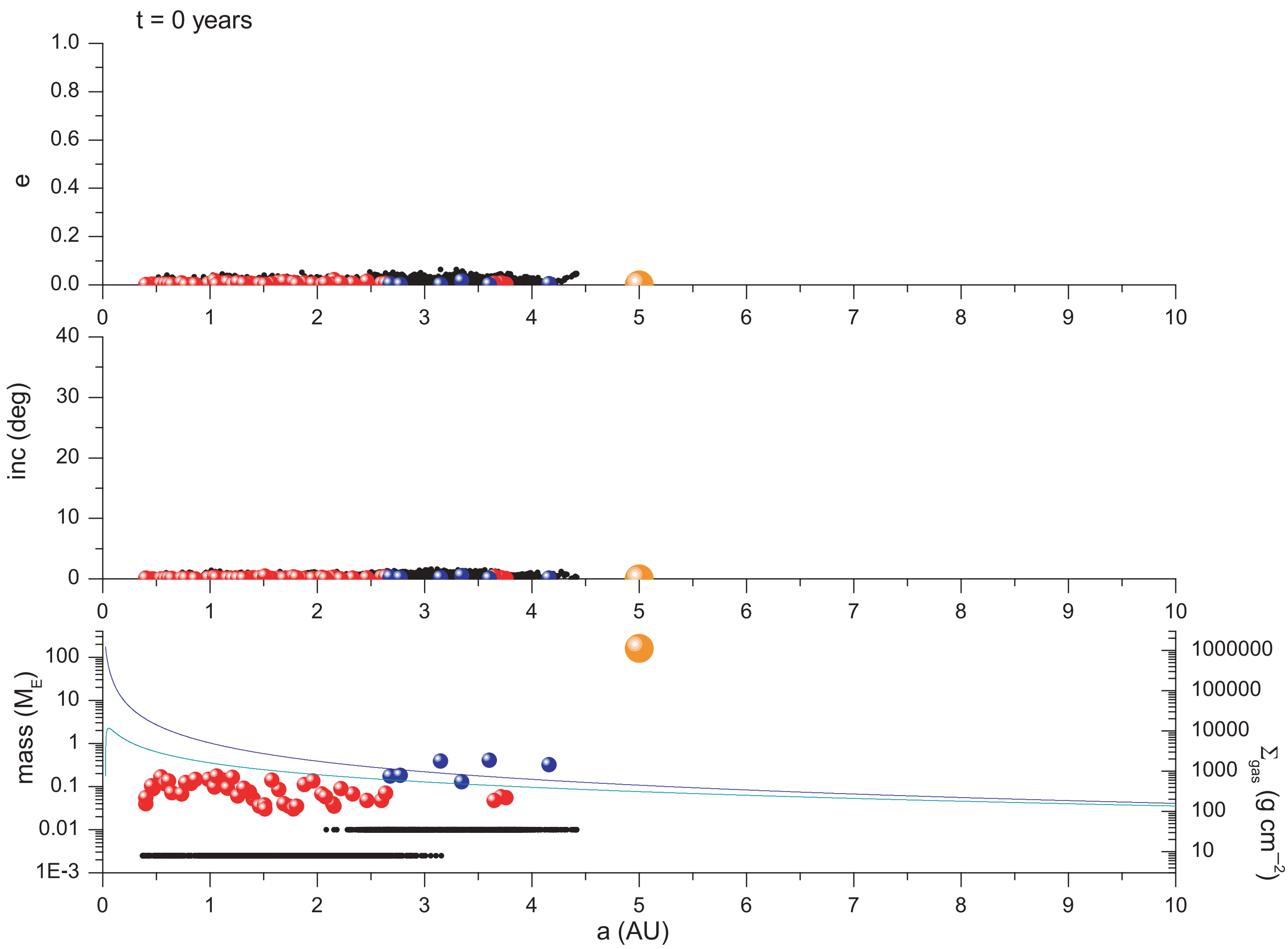

Fig. 2. The example scenario shown at $t = 0$, the instant the giant planet is inserted, showing on the left-hand axes the eccentricity, inclination and mass of particles and on the right-hand axis, the surface density of the gas disc. Red-filled circles represent rocky protoplanets, blue-filled circles represent icy protoplanets and the larger yellow-filled circle represents the giant planet. Black dots represent superplanetesimals. The upper gas density curve is the original profile for a $3 \times$ MMSN model and the lower curve denotes the evolved profile.

inward to 3.06 AU and its effects are also apparent on the population of solid bodies. The migrating giant shepherds the disc inwards at the 4:3 mean motion resonance currently at 2.53 AU. This occurs because the resonant locking causes the semi-major axes of objects to decrease and also causes their eccentricities to grow; the eccentricity growth of planetesimals is limited by gas drag. Protoplanets and planetesimals are also shepherded at other strong first-order resonances and this is well demonstrated in the top panel at 1.93 AU where eight protoplanets are captured at the 2:1 resonance with their eccentricities pumped to moderate or high values. This resonant excitation is mostly responsible for generating the population of scattered objects that are seen to be accumulating in orbits exterior to the giant planet. Once an object's orbit is excited to the extent that it intersects the orbit of the giant (the area between the two dotted lines in the upper panel of Fig. 3), a series of scattering encounters occur, typically resulting in eventual expulsion into a higher, non-intersecting orbit.

The state of the system at $t = 80\,000$ years is shown in Fig. 4. The giant planet is now at 1.20 AU, having ploughed through more than three quarters of the original width of the solids disc. An extensive scattered population is now accumulating in higher orbits and four protoplanets whose orbits cross that of the giant are seen to be in various stages of being fed through into the scattered disc. A substantial fraction of the original material remains interior to the giant and has been compacted to high surface densities. This speeds up accretion and one protoplanet has grown to 0.82 $m_{\oplus}$. Once protoplanets start to become large, perturbations between them, and on planetesimals, can also serve to scatter material, via the giant, into external orbits.

The simulation is terminated at $t = 106\,000$ years[4] when the giant planet has reached 0.1 AU, and this point is illustrated in Fig. 5. The original solids disc has been partitioned into an extensive scattered remnant in exterior orbits and an interior remnant consisting principally of a single 4.04 $m_{\oplus}$ planet.

[4] The difference between this migration timescale and the longer 170 000 years obtained in Fogg & Nelson (2005) arises from an alternative nebular gas scale height chosen for our evolving gas disc model.

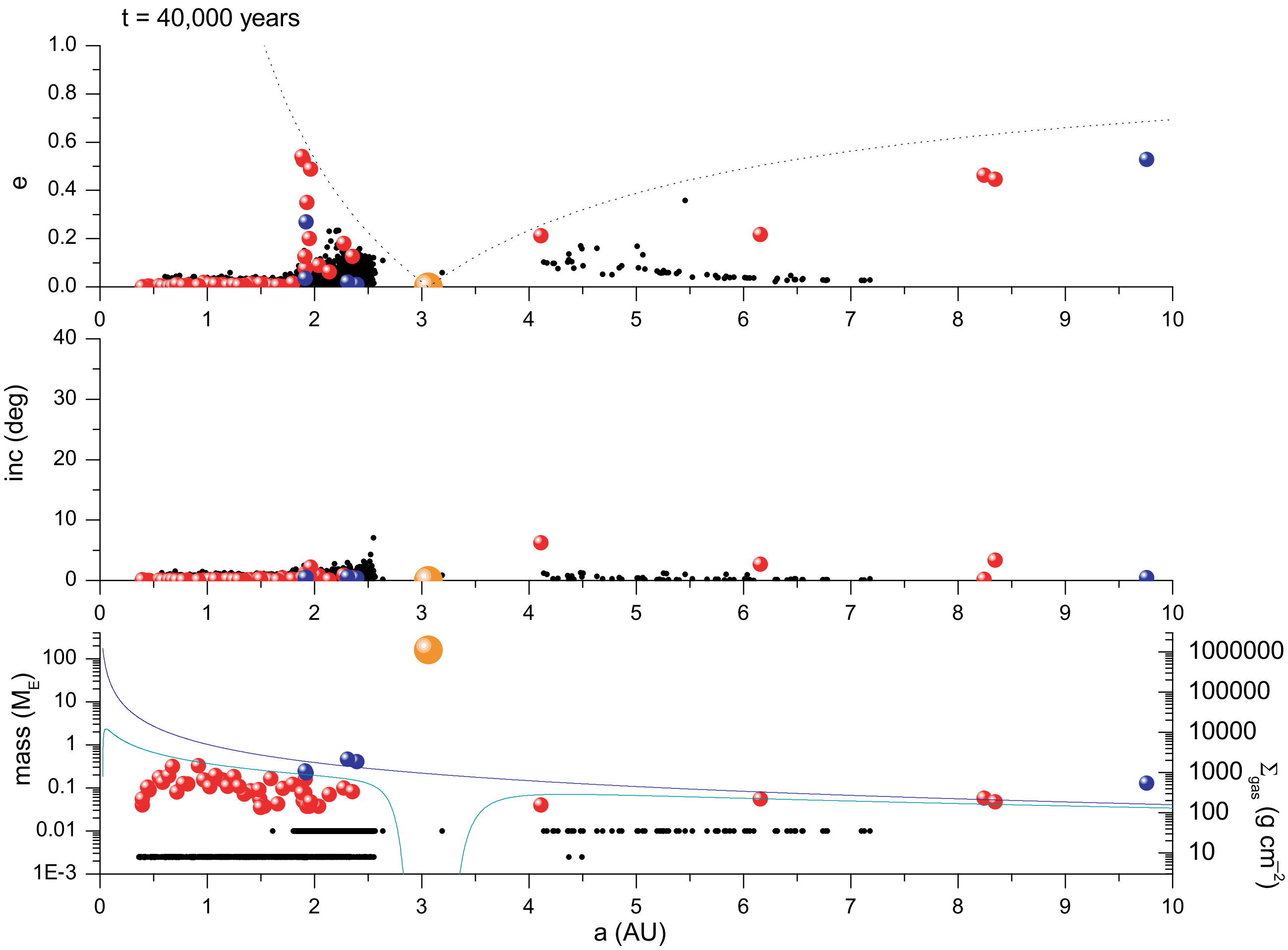

Fig. 3. The example scenario at $t = 40\,000$ years. Any object lying between the two dotted curves in the upper panel has an orbit that crosses that of the giant planet. The giant has formed a gap in the nebular gas and has migrated inward to 3.06 AU. Shepherding of the solids disk at the 4:3 resonance and excitation of the orbits of protoplanets captured at the 2:1 resonance is evident in the top panel.

This object is reminiscent of the 'hot-Neptune' type planets generated by the simulations in Fogg & Nelson (2005); however, in this case it is positioned at 0.076 AU, in the 3:2 resonance, with an eccentric orbit almost intersecting that of the giant. The usual outcome for this type of configuration when it is run for a longer period of time is that the interior planet is eventually accreted by the giant or scattered out to ~0.4 AU. Details of the fate of the disc mass at the end of the simulation are given in Table 1. These data show that 76% of the disc mass survives the migration of the giant planet, with 60% of the original mass being found in the scattered disc. There is negligible loss of solid material to the central star (taken to have a radius of 0.014 AU) or by ejection from the system. The 24% of the original disc that was lost was accreted by the giant planet[5]. Replacement of the steady-state gas disc assumed by Fogg & Nelson (2005) with the evolving gas disc shown in this example has the effect of reducing the fraction of disc mass that remains interior to the giant or is lost to the central star and increasing the mass that is scattered or accreted by the giant. Having now computed a series of these new models at varying stages of disc maturity (Fogg & Nelson 2006), we find that 60–80% of the original, inner system, solids disc survives in external orbits in each case.

[5] Note that we assume no further gas accretion onto the giant after its insertion into the simulation.

The scattered disc, as illustrated in Fig. 5, shows three obvious features:

(1) the disc is partially dispersed as some mass has been scattered beyond its original outer edge at 4 AU;
(2) sufficient gas remains to rapidly damp planetesimal orbits, lowering their eccentricities to $e < 0.1$; and
(3) the orbits of scattered protoplanets are typically inclined and non-circular, with eccentricities averaging at $e \approx 0.5$.

Although the scattered disc looks well populated in Fig. 5, it is not so obvious how the surface density of the remaining material compares with that of the original undisturbed disc. This comparison, made by summing the mass and dividing by the area in 0.1 AU width bins, is shown in Fig. 6, where the grey curve gives the initial solids surface density profile and the black curve gives the profile at the end of the run. The principal differences between the two curves are the mass augmentation of the 'initial' curve beyond 2.5 AU,

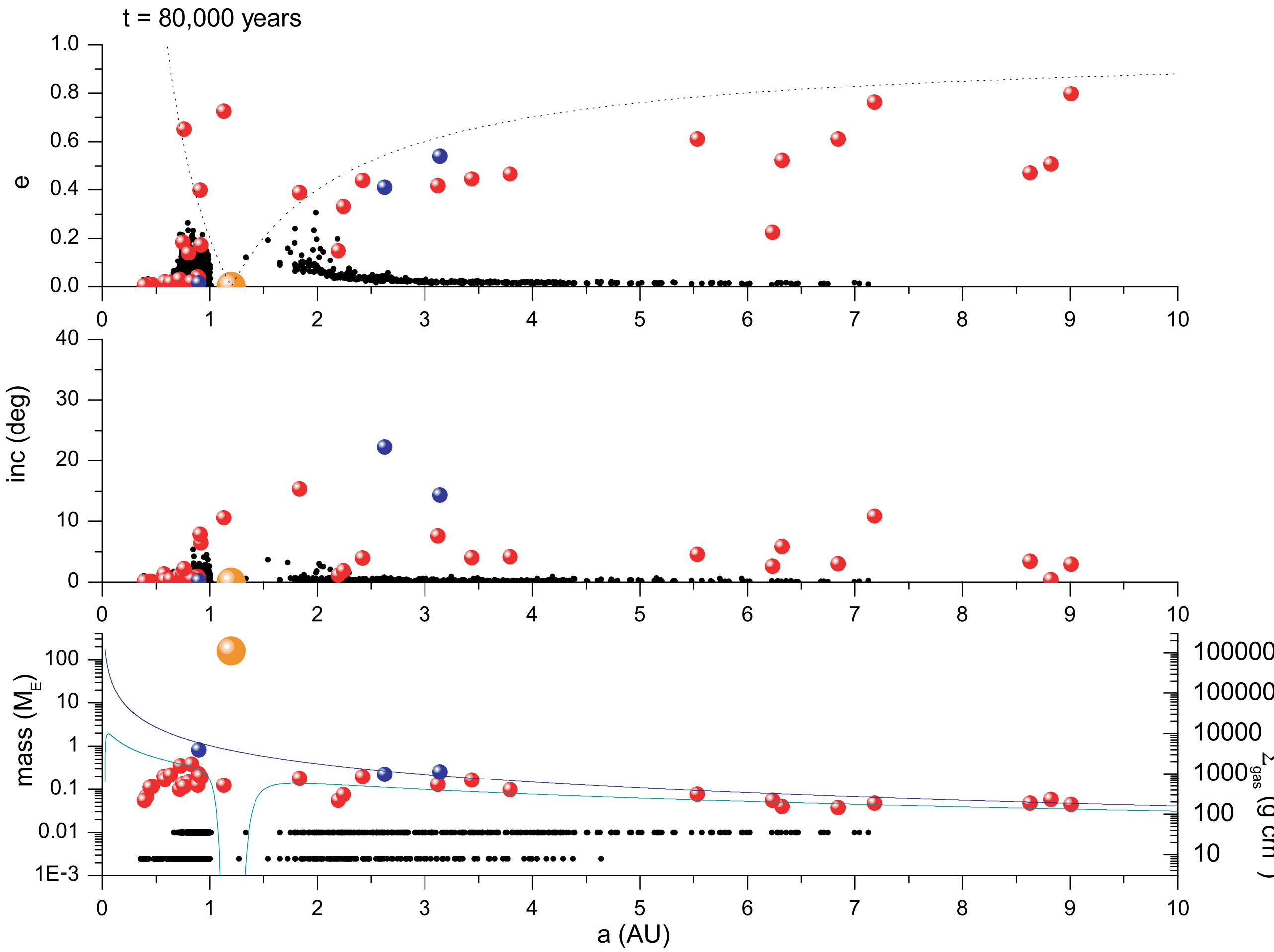

Fig. 4. The example scenario at $t = 80\,000$ years. The giant has now migrated inward to 1.20 AU. A disc of scattered protoplanetary and planetesimal material is building up in external orbits. Four protoplanets are seen to be currently crossing the orbit of the giant planet and are in the process of being fed into the scattered disc.

representing icy matter condensed beyond the snowline, and the two large spikes on the 'end of run' curve, which are largely caused by the presence of two newly-accreted large planets (a 4.04 $m_\oplus$ planet at 0.076 AU and a 1.68 $m_\oplus$ planet at 0.85 AU). However, if we ignore this latter spike at 0.85 AU, it is noticeable that the amount of solid matter between 0.5 and 1.5 AU at the end of the run is little changed from its initial values. The amount of mass beyond 2.5 AU is significantly reduced though, implying that a large quantity of volatile-rich material has been driven into the inner system.

Since ample material remains in the inner system to build a set of terrestrial planets, what are the chances of this happening? The high eccentricities of surviving protoplanets are a worry as their high random velocities slow growth by reducing their capture cross sections and could encourage disruptive, rather than accumulative, collisions (Agnor & Asphaug 2004). However, 60% of the mass of the scattered disc shown in Fig. 5 remains in planetesimals, so dynamical friction should still be effective at damping protoplanet orbits. While we have not yet run a full accretion simulation of one of these scattered discs (which would involve a two order of magnitude extension of simulated time), exploratory runs have shown that the orbits of the larger protoplanets at less than 2 AU circularize within ~1 Myr and robust growth resumes. Some degree of orbital circularization would also be expected for protoplanets scattered to more distant orbits as they encounter material from the outer disc, beyond the giant planet's original formation position.

If the future evolution of scattered discs does lead to net accumulation, then a set of terrestrial planets should form in orbits external to hot-Jupiters, in a similar manner to that presented by Raymond *et al.* (2005). However, we predict that these planets will form from original inner disc material that has been well mixed with volatile-rich material from beyond the snowline. If, as seems likely, one or more planets do form in the HZ, then the existence of 'water worlds' is a distinct possibility (Kuchner 2003; Léger *et al.* 2004).

Conclusions

The modelling of the problem of terrestrial planet formation in the presence of and following giant planet migration is still

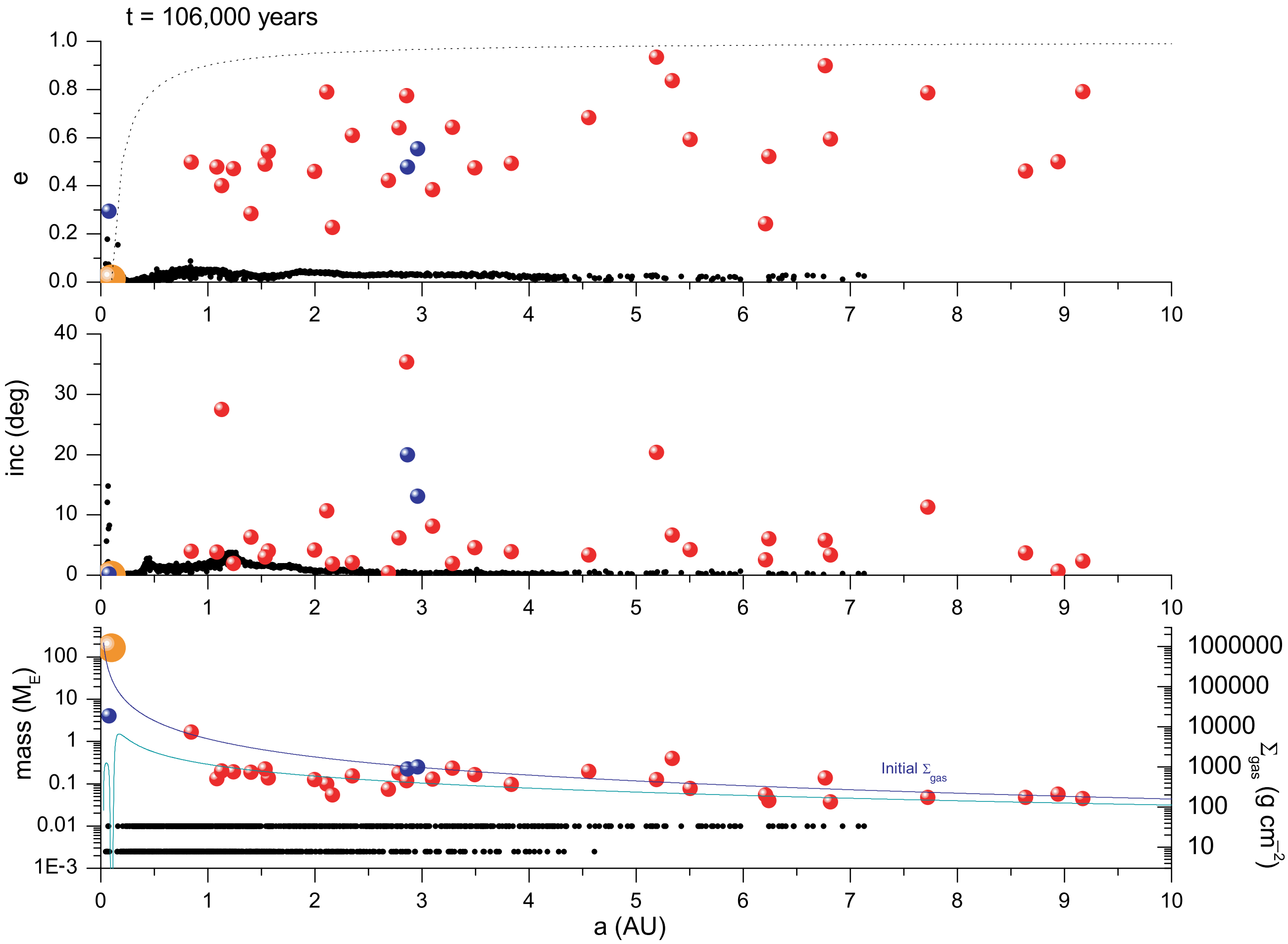

Fig. 5. The example scenario at $t = 106\,000$ years, when the giant planet reaches 0.1 AU. The majority of the disc solids have survived the migration episode; 60 % of the original disc mass now resides in the scattered disc and is potentially available for renewed planetary growth.

Table 1. *Fate of the disc mass at the end of the example scenario*

Initial solids mass	24.81 $m_\oplus$ (100 %)
Total surviving solids	18.88 $m_\oplus$ (76 %)
Interior surviving solids	4.06 $m_\oplus$ (16 %)
Exterior surviving solids	14.82 $m_\oplus$ (60 %)
Accreted by star	0 $m_\oplus$ (0 %)
Accreted by giant	5.84 $m_\oplus$ (24 %)
Ejected	0 $m_\oplus$ (0 %)

at its early stages and is largely based on conjecture as to how hot-Jupiters form and arrive at their final orbits. Assuming that the type II migration scenario is the correct one, then its parameter space should be further explored, including study of the effects of varying the mass of the giant and its migration time and the incorporation of more detailed physics such as planetesimal size evolution and possibly alternate migration modes that affect smaller bodies such as type I migration (Ward 1997; Papaloizou & Larwood 2000). All the studies to date that have actually modelled the effects of giant planet migration, rather than assuming the effects as an initial condition, predict that some inner system material

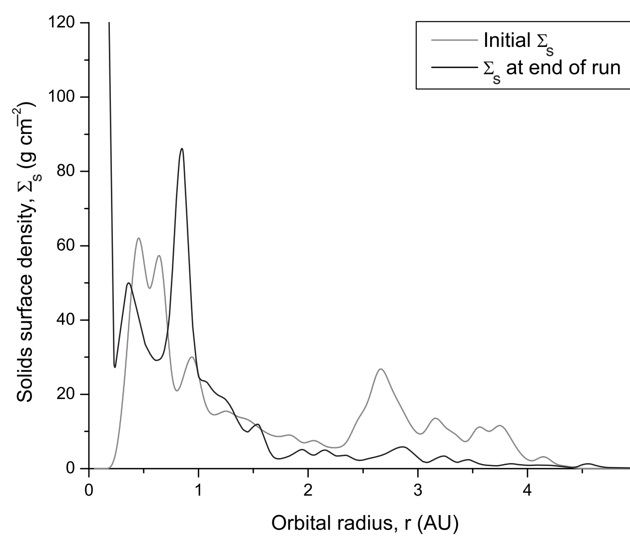

Fig. 6. The surface density of solid material, including both protoplanets and planetesimals, at the beginning of the simulation (the grey curve) and at the end (the black curve). Ample material remains at less than 2 AU to provide for future terrestrial planet formation.

traversed by the giant will survive (Mandell & Sigurdsson 2003; Fogg & Nelson 2005; Fogg & Nelson 2006). For migration times of ~0.1 Myr, a majority of the disc solids are predicted to remain after the migration episode with sufficient matter remaining for renewed planetary growth, especially in the region between 0.5 and 2 AU. Since this region contains the HZ for G class stars, the presence of Earth-like planets in hot-Jupiter systems cannot be ruled out.

Rare Earth-type predictions that hot-Jupiter systems are barren are based on an *ex cathedra* assumption that this is so and not on any modelling of the likely processes involved. The results of detailed modelling suggest that these predictions may be overly pessimistic. Future space-based observatories, such as the proposed 'Darwin' infrared interferometer (Kaltenegger & Fridlund 2005), may provide a definitive answer to this question within the next decade.

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