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The Formation of Mars: Building Blocks and Accretion Time Scale

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Abstract In this review paper I address the current knowledge of the formation of Mars, focusing on its primary constituents, its formation time scale and its small mass compared to Earth and Venus. I argue that the small mass of Mars requires the terrestrial planets to have formed from a narrow annulus of material, rather than a disc extending to Jupiter. The truncation of the outer edge of the disc was most likely the result of giant planet migration, which kept Mars' mass small. From cosmochemical constraints it is argued that Mars formed in a couple of million years and is essentially a planetary embryo that never grew to a full-fledged planet. This is in agreement with the latest dynamical models. Most of Mars' building blocks consists of material that formed in the 2 AU to 3 AU region, and is thus more water-rich than that accreted by Earth and Venus. The putative Mars could have consisted of 0.1 % to 0.2 % by mass of water.

Keywords Mars · Formation · Origin

1 Introduction

The formation of the terrestrial planets of the Solar System has been an outstanding problem for a long time. Significant progress has recently been made with the aid of fast computers and has led to a coherent picture and sequence of events. Put simply, the terrestrial planets formed from the accumulation of many planetesimals whose sizes ranges from hundreds of meters to hundreds of kilometres. This process has been shown to take of the order of 100 million years (Myr) (e.g. Chambers 2001; Kokubo and Ida 1998), with the Moon-forming event being the last giant impact on the Earth (Kleine et al. 2009), some 60 Myr after the formation of the Solar System.

Even though many successes have recently been made, the small size of Mars (and also Mercury) has been a sticking point for a long time (e.g. Chambers 2001; Raymond et al. 2009). In this chapter I shall review some of the recent progress that has been made towards

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understanding the formation of the terrestrial planets, in particular focusing on the formation of Mars. A more thorough review of terrestrial planet formation can be found in Morbidelli et al. (2012). This chapter has been divided into the following sections. Section 2 gives an overview of terrestrial planet formation from a dynamical point of view. In Sect. 3 I shall focus on terrestrial planet formation from a narrow annulus, which appears to be able to reproduce the small masses of Mercury and Mars. The next section deals with the so-called 'Grand Tack' scenario, which invokes the migration of the giant planets Jupiter and Saturn to dynamically truncate the outer edge of the disc from which the terrestrial planets eventually formed. Section 5 is devoted to present cosmochemical evidence in support of the fact that Mars might be a left-over planetary embryo, as is suggested from the annulus and Grand Tack formation scenarios. In Sect. 6 I shall present a summary and conclusions.

2 An Overview of Terrestrial Planet Formation

Terrestrial planet formation proceeds through three main stages, with some overlap between them. The first stage is believed to be the settling of dust in the midplane of the solar nebula, which then accretes together to form small bodies called 'planetesimals'. This phase is not well understood, and there are several competing ideas suggesting that planetesimals either form small and systematically grow through collisions (e.g. Weidenschilling and Cuzzi 1993; Wurm et al. 2001) or that they form big (∼100 km) through gravitational instability (e.g. Johansen et al. 2007) or by turbulent concentration (Cuzzi et al. 2008). What is important to point out is that once the planetesimals have reached a critical size of a few kilometres, their gravitational influence on each other is strong enough that they begin to scatter each other onto crossing orbits. This is when the second phase kicks in.

Safronov and Zvjagina (1969) pointed out that available planetesimals are systematically accumulated into fewer but larger bodies (Greenberg et al. 1978). If left unchecked, and assuming that the accretion occurs locally, all the material would eventually collide together to form a planet out of a small feeding zone. The size of this feeding zone grows slowly as the mass of the planet increases and scales with the mass of the planet as $m_p^{1/3}$. This growth process is called 'runaway accretion' because effectively $\dot{m}_p \propto m_p^{\alpha}$ and exponential growth ensues. The relative velocity between the planetesimals is governed by encounters between them. The masses of the planetesimals are very low and so their relative encounter velocities, increased slowly through self-stirring, are much lower than their orbital speeds. Once one of the planetesimals has accumulated more mass than its neighbours by colliding with another planetesimal, its gravitational cross section and mass also grow. This allows it to accrete more material from its surroundings because its feeding zone has increased in size. The stage of runaway growth typically lasts less than 1 Myr at 1 AU from the Sun (Kokubo and Ida 1995). This simple picture leads one to believe that the terrestrial planets Mercury, Venus, Earth and Mars, all grew from material that was accreted locally. As I shall show later, this is most certainly not the case.

The simple picture of local runaway accretion described above breaks down when the mass of the largest body, a 'protoplanet' or 'planetary embryo', is significantly larger than the mass of nearby planetesimals. Once a protoplanet has accreted most of the planetesimals in its vicinity, the remaining planetesimals are no longer able to damp their mutual velocities and the gravitational cross section for accretion onto the protoplanet decreases. By now the relative velocity of the planetesimals is dominated by encounters with the protoplanet rather than themselves. The encounters with the protoplanet increase the relative velocity of the planetesimals, which results in a decrease in the gravitational cross section for collision with the protoplanet. At this stage the protoplanet essentially stops its runaway growth phase and its accretion rate decreases significantly. This allows neighbouring, less massive protoplanets to catch up with the most massive protoplanet since the relative velocity of the planetesimals in their vicinity is lower than that around the most massive protoplanet. The next protoplanet catches up with the first one, and this process continues until the system reaches equilibrium which consists of a large number of roughly equal-mass protoplanets that are almost evenly spaced. The combined mass of the protoplanets is similar to the remaining mass in planetesimals. The protoplanets still accrete the planetesimals but they are all forced to grow at a similar pace. This growth phase of the protoplanets is dubbed 'oligarchic growth' (Kokubo and Ida 1998). The typical size of these protoplanets is Mercury to Mars sized and the time to reach this stage is shorter than 10 Myr (Kokubo and Ida 1998).

The system consisting of a large number of oligarchs and planetesimals is stable as long as the mass in planetesimals is larger than or equal to that of the protoplanets. The reason for this is that the planetesimals damp the eccentricities and inclinations of the protoplanets through angular momentum and energy partitioning, and this process is called 'dynamical friction' (Ida and Makino 1993). The disc starts with a certain angular momentum and energy budget. The protoplanets scatter the planetesimals onto eccentric orbits, decreasing the angular momentum budget in the planetesimals and increasing their orbital energies. The conservation of angular momentum implies that the protoplanets gain the angular momentum that the planetesimals have lost. Similarly the energy that the planetesimals have gained is compensated by a loss in energy of the protoplanets. Once the planetesimal reservoir is depleted, mutual perturbations of the protoplanets tend to increase their eccentricities and inclinations and eventually their orbits begin to cross. This instability is the onset of the third and last stage of terrestrial planet formation: the final terrestrial planets grow through mutual collisions of the protoplanets and the remaining planetesimals, which decreases the number of objects. This third stage is characterised by violent, stochastic, large collisions, one of which formed the Earth's Moon (Canup 2004). Eventually all the protoplanets have collided with one another and one is typically left with 3 to 5 terrestrial planets (Chambers 2001; O'Brien et al. 2006; Kokubo et al. 2006; Raymond et al. 2006, 2009).

The reason we generally find between 2 to 6 (mostly 3 to 5) terrestrial planets is partially the result of constrained formation and initial conditions. An earlier work by Kominami and Ida (2002, 2004) studied terrestrial planet formation from protoplanets in the presence of gas drag that was left from the primordial solar nebula in the range $\sim$0.6 AU to $\sim$1.7 AU. They generally formed 7 terrestrial planets of sub-terrestrial mass. The most likely reason for this higher number of planets is that the gas drag damped the eccentricity of the protoplanets strongly enough to prevent long-term orbit crossing and thus the violent mutual collisions that characterise the third stage. However, the final number of planets in the simulations is partially a result of the initial conditions. Extending the embryos close to Jupiter ($\sim$4 AU) does not change the outcome because the secular resonance ν_6 at 2 AU and the strong perturbations from Jupiter in the asteroid belt present an effective barrier for terrestrial planet formation beyond $\sim$1.8 AU (O'Brien et al. 2006). Most studies have truncated the inner edge of the disc, typically at 0.5 AU to 0.7 AU (Kokubo and Ida 1998; Hansen 2009; Raymond et al. 2006, 2009) or decreased its density profile inwards of 0.7 AU (Chambers 2001; O'Brien et al. 2006). Hence the amount of mass on the Sunward side was artificially restricted. In addition, most studies used a surface density value $\Sigma \sim 7\ \mathrm{g\,cm^{-2}}$, and the number of planets does not sensitively depend on this result (Kokubo et al. 2006).

In Fig. 1 I plot a series of snapshots of a simulation of terrestrial planet formation i.e. runaway growth, oligarchic growth and the final collisions. The picture displays the semi-major axis (a) and eccentricity (e) of the protoplanets and planetesimals. The size of the

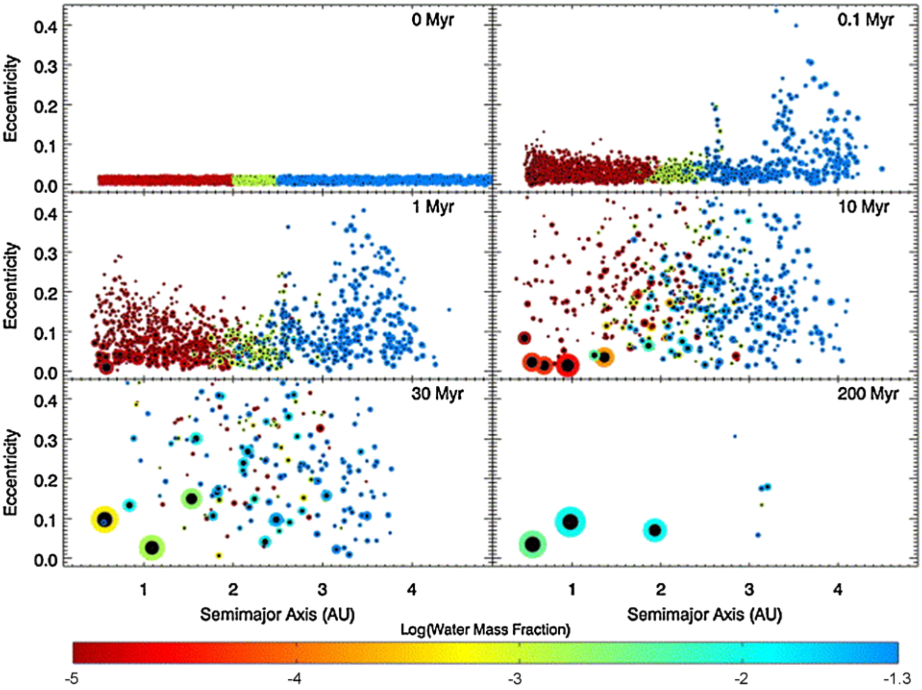


Fig. 1 Sample evolution of terrestrial planet formation. The size of each bullet scales as the mass of the object, $m^{1/3}$ and the colour is an indication of its original location. Taken from Raymond et al. (2006)

bullets representing the protoplanets in the figure, scale as their mass $m_p^{1/3}$. The colour coding in Fig. 1 denotes the initial position of each planetesimal and the final colouring of each (proto)planet is a measure of its consituents.

The simulations start with a disc which consists of a large sample of planetesimals spread out between 0.5 AU and 4.5 AU. The planetesimals perturb and collide with each other and after 1 Myr we see the formation of a few protoplanets. The protoplanets form from the inside out because the orbital time scale, and thus the collision time scale, is shorter close to the Sun than far away. After 10 Myr the system consists of a few tightly-packed red protoplanets in the inner region and a variety of smaller protoplanets farther out, all on eccentric orbits. The planetesimals are all over the place. A further 20 Myr later the number of protoplanets has decreased and the remaining ones have grown in mass. In addition, their composition has changed. Even the innermost protoplanet is no longer completely red but has become yellow, implying it has accreted material from outside its feeding zone. This radial mixing of material is an important outcome of simulations of terrestrial planet formation and could account for Earth's water content. I shall return to this topic in Sect. 4. Finally, 200 Myr after the start of the simulation, the system consists of a few remaining planetesimals and three terrestrial planets situated between 0.5 AU and 2 AU.

What is important to note is that the masses of all three terrestrial planets are comparable, as distinguished from the size of their bullets in Fig. 1. One can perform many more simulations of terrestrial planet formation with various initial conditions to determine how the end result depends on the initial conditions, but there appears little variety: there are almost always three or five planets between 0.5 AU and 2 AU with the middle two planets having masses similar to Venus and Earth (Kokubo et al. 2006; Raymond et al. 2006, 2009;

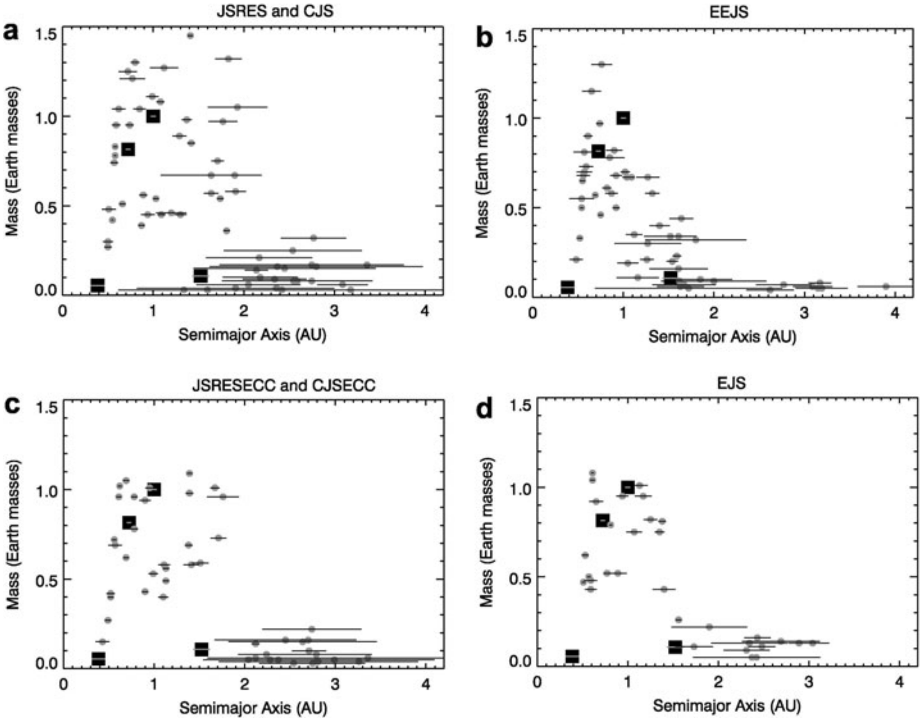
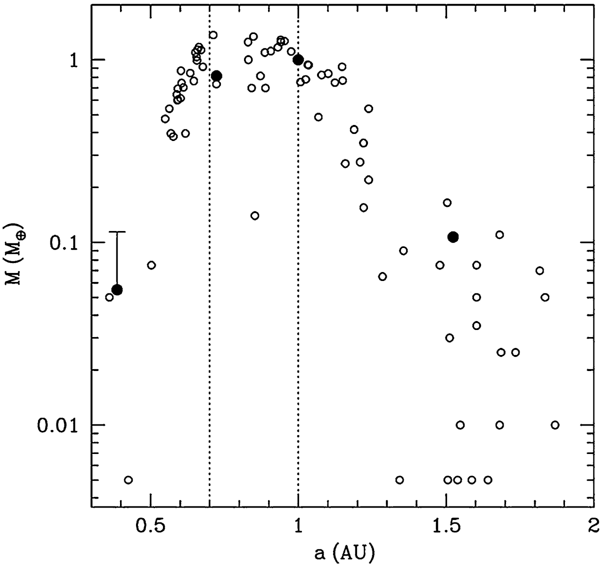


Fig. 2 Mass vs semi-major axis for a range of end states of terrestrial planet formation. Taken from Raymond et al. (2009)

O'Brien et al. 2006). However, the inner and outer planet are systematically much heavier than Mercury and Mars. Even though most of the simulated systems are compatible with the terrestrial planets in terms of their Angular Momentum Deficit (AMD)—a measure of the deviation from circular, coplanar orbits—and the spacing between the planets is also well reproduced, the concentration of mass is not.

The final masses versus semi-major axes of the end states of several terrestrial planet formation simulations from Raymond et al. (2009) are plotted in Fig. 2. This figure shows all the planets that were formed in 40 simulations, but the reader should be aware that most systems contain 3 to 5 terrestrial planets. Each panel of the figure pertains to a different configuration of Jupiter and Saturn (see Raymond et al. 2009). The terrestrial planets of our Solar System are depicted with filled squares while the masses of the planets formed in the numerical simulations are depicted by grey bullets. Even though the masses of Venus and Earth are reproduced at their current locations, Mercury and Mars are not. From the figure one can see that the masses of the planets and their locations are systematically too high. Apart from the panel labelled 'EEJS', where Jupiter and Saturn are placed on more eccentric orbits than their current values (currently $e_J = 0.05$, $e_S = 0.06$), the small mass of Mars is not reproduced. In many simulations a Mars-mass planet remains on an eccentric orbit, but it is farther from the Sun than Mars is today. Planets at the present location of Mars are almost always more massive, typically 0.2 to 0.6 Earth masses ($M_\oplus$). Since there is no evidence for Jupiter and Saturn ever having had larger eccentricities than currently for a prolonged period of time (Morbidelli et al. 2010), we must conclude that current terrestrial planet formation simulations have great difficulty reproducing the mass of Mars.

Fig. 3 Mass vs semi-major axis for a range of end states of terrestrial planet formation from a narrow annulus, originally between 0.7 AU and 1 AU. Taken from Hansen (2009). *Black bullets* are the Solar System planets



Chambers (2001) already noted that it was difficult to reproduce the mass of Mars in terrestrial planet formation simulations. He argued that the high mass concentration in Venus and Earth can only be explained in two ways: either in the regions occupied by Mars and Mercury the surface density of the disc was lower than at Venus and the Earth, or mass was lost from the system in these regions during the accretion of the terrestrial planets. Figure 1 above shows that the second option, losing mass from the region that Mars now occupies, does not occur, so we are left with the first: the surface density of the disc of material from which the terrestrial planets formed was lower at the present position of Mars than it was at Earth and Venus.

So, let us examine how terrestrial planet formation would proceed when the source material is confined to the Venus-Earth region.

3 Terrestrial Planet Formation from a Narrow Annulus

Hansen (2009) has examined the formation of the terrestrial planets starting from an annulus of material with constant surface density between 0.7 AU and 1 AU. He examined the evolution of a system of 400 equal-mass planetesimals on essentially circular and coplanar orbits, essentially only studying the third stage of terrestrial planet formation. The total mass in the system is 2 $M_\oplus$. The gas giant Jupiter was included in the simulations. After integrating this system for 1 Gyr, Hansen (2009) is left with either 3 or 4 terrestrial planets whose spacing and AMD match the current terrestrial planets and he was also able to reproduce the small masses of Mercury and Mars because these regions were originally depleted in material.

Figure 3, taken from Hansen (2009), is similar to Fig. 2 in that it depicts the mass versus semi-major axis of all the terrestrial planets that were formed from his simulations. The current terrestrial planets are depicted by filled circles while the open circles are fictitious planets from the simulations. As can be seen, the planets at 1.5 AU typically have the same mass as Mars while Mercury is marginally reproduced. Another interesting feature of Hansen's simulations is the fact that the planets on the edges (Mercury and Mars) are

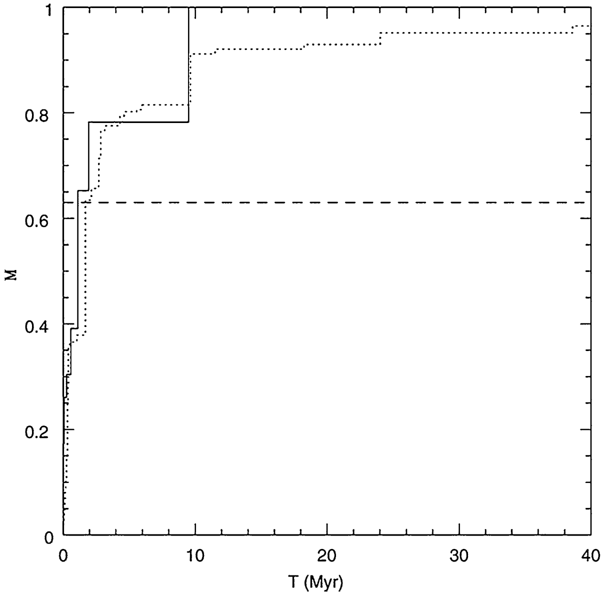


Fig. 4 Mass vs time for a Mars-sized analogue. Taken from Hansen (2009)

systematically more eccentric and inclined than the two central planets (Earth and Venus), similar to the Solar System. This suggests that the former two were scattered out of the disc and essentially remained there without subsequently accreting much more material. Indeed, this is what Hansen (2009) claims to have happened, arguing that both Mars and Mercury are protoplanets that ceased to grow to full-fledged terrestrial planets because of a lack of material to accrete in their direct surroundings. If true, then the growth of Mars (and Mercury) should have occurred very quickly in the beginning and essentially stopped shortly afterwards. Figure 4 depicts the mass of a Mars-sized planet (solid) line, and that of an Earth analogue (dotted line). As one may see, the Mars-sized planet stops growing approximately 10 Myr after the onset of the third stage. Since the second stage usually takes up a fraction of this time, the formation of Mars roughly coincides with the time that oligarchic growth has finished and the third phase of terrestrial planet formation commences. By comparison, in the simulations the Earth was still growing after 40 Myr, and did not reach its final mass until much later (Hansen 2009). What is also interesting to note is that the growth of both planets, while rapid at first, slows down but occurs in discrete steps rather than continuous growth. These sudden increases in mass coincide with collisions with other protoplanets, which tend to dominate the long-term behaviour.

3.1 Caveats

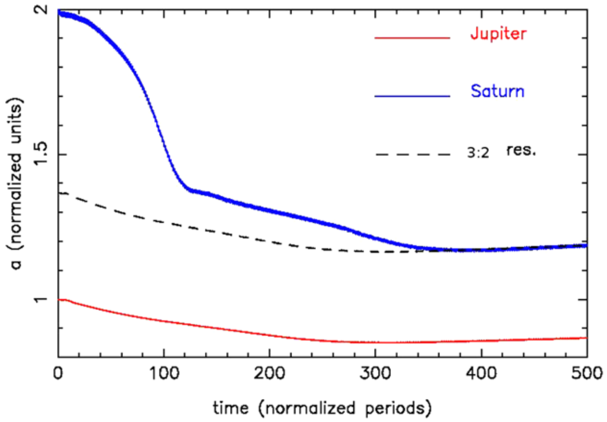
It appears as if terrestrial planet formation from a narrow annulus is able to solve a long-lasting problem in planetary science: the small mass of Mars (and that of Mercury) compared to the Earth. The annulus formation scenario also explains why Mercury and Mars are more inclined and eccentric than the Earth and Venus, and the number of planets, the mass concentration, spacing and AMD of the resulting planets all match the current terrestrial system well. However, there are two problems that need to be addressed. First, the formation of the terrestrial planets from an annulus cannot account for the water on Earth because the material this close to the Sun is essentially dry (e.g. Sasselov and Lecar 2000). Thus the water either had to be delivered later, or the annulus had to be wetter than most theories seem to suggest. Secondly, what caused the disc to be truncated? The existence of an inner edge can be explained by the migration of close-in protoplanets. These formed when the gas was still present in the solar nebula (Ida and Lin 2008). The time scale of the formation of protoplanets is proportional to their distance to the Sun, and thus the protoplanets form quicker closer to the Sun than further out. As the gas is depleted, the protoplanets stop migrating into the star and some of these remain behind. Beyond a threshold distance, the planetesimal disc remains intact because no protoplanets have yet formed and no migration has yet occurred. Ida and Lin (2008) demonstrate that this inner edge is typically around 0.5 AU to 1 AU. It could be argued that this migration scenario can be used to explain the small mass of Mercury, which is always difficult to reproduce in numerical simulations. Recent results from the volatiles at Mercury measured by the MESSENGER mission suggest that it did not suffer a giant impact which stripped its mantle nor could this stripping have occurred through solar heating (Peplowski et al. 2011), so that its formation location is uncertain. That said, the formation of Mercury is not fully understood and discussing it is beyond the scope of this paper.

However, there is no natural explanation for the existence of an outer edge of the planetesimal disc apart from it arising through a dynamical origin. Hansen (2009) concluded that a very sharp, almost discontinuous edge was needed; a Gaussian density distribution was not sufficient. The disc could not have been truncated by photoevaporation because this would have prevented the formation of the giant planets farther out than where the disc was truncated. Likewise, a truncation through a close stellar passage can also be ruled out because this would either have prevented the formation of the giant planets or destabilised an existing giant planet system. Other possibilities include a steeper decline in the surface density of the disc in Mars' region than closer in Chambers and Cassen (2002), particle pile-up through turbulent stirring (Haghighipour and Boss 2003; Johansen et al. 2007), or even a planet trap (Masset et al. 2006). A planet trap is a place in the gas disc where there is a steep surface-density gradient; this steep gradient prevents giant planet migration. However, none of these theories has been particularly favoured nor accepted by the community. Therefore we explore another, more generic possibility: dynamical sculpting by migration of Jupiter and Saturn.

4 The Grand Tack Scenario

Masset and Snellgrove (2001) demonstrated that when Jupiter and Saturn formed in the gaseous protoplanetary disc, well before the formation of the terrestrial planets, both migrated towards the Sun. The migration of the giant planets in a gas disc is a generic outcome of planet formation. The migration is illustrated in Fig. 5. In this simulation, Jupiter is massive enough to open a cavity in the disc, and thus its migration time scale is tied to the viscous evolution of the disc (Type II migration; Papaloizou and Lin 1984). On the other hand, Saturn is not massive enough to open a complete cavity and thus its migration speed is much faster (Type I migration; Goldreich and Tremaine 1980). Both planets move inwards because of the asymmetric Lindblad torques generated from spiral wakes. As can be seen, the migration of Jupiter ceases when Saturn falls into the 2 : 3 mean motion resonance with Jupiter i.e. when Saturn performs two orbits for every three of Jupiter. In fact, the migration even reverses direction! This reversal occurs because the proximity of Saturn to Jupiter causes the cavities they open up in the gas disc to overlap (Morbidelli and Crida 2007), and the asymmetry of the gap cancels and reverses the torques. This reversal of migration is

Fig. 5 Migration of Jupiter and Saturn in a gas disc. Taken from Masset and Snellgrove (2001)



once again a generic outcome, since the probability of Saturn getting caught in the 2 : 3 resonance with Jupiter is high (Pierens and Nelson 2008). It should be noted that the slowing of Jupiter's migration and even its reversal is only possible because Saturn is less massive than Jupiter; if the situation was reversed, both planets would migrate into the Sun because the outer, more massive planet would push the inner, less massive one Sunwards. In our system, it is possible that Jupiter and Saturn migrated inwards far enough to truncate the disc of material from which the terrestrial planets formed before migrating out again. All that needs to be specified is the turning point, which is described in Walsh et al. (2011) and is called the 'Grand Tack' scenario. Here I will just give a short summary of its workings.

The Grand Tack scenario relies on two assumptions: Jupiter formed around the snow line, in the range 2.5 AU to 4.5 AU, and it reversed migration at 1.5 AU. Walsh et al. (2011) demonstrate that the asteroid belt can survive this migration of Jupiter and Saturn because scattering by Jupiter initially empties the belt when it migrates inwards, but then repopulates the asteroid belt as it migrates outwards. The reversal at 1.5 AU of Jupiter truncates the disc at 1 AU, effectively creating Hansen's (2009) annulus. Figure 6 shows the migration of the giant planets in the reference simulation of Walsh et al. (2011) as well as the growth of their masses. After 0.1 Myr Saturn catches up with Jupiter, falls into the 2 : 3 resonance and they reverse their migration. Eventually all four giant planets end up in a multi-resonant configuration on nearly-circular, coplanar orbits, similar to the resonant initial conditions of the Nice model (Morbidelli et al. 2007).

The workings of the Grand Tack scenario are illustrated in Fig. 7. Here the planets are outlined by large, filled bullets, with sizes scaling as the mass and the planetary embryos and terrestrial planets are depicted using open circles. The blue dots are water-rich planetesimals from the outer solar system i.e. from beyond the snow line (beyond 3 AU). These are left over from giant planet formation. The red dots are water-poor planetesimals from the inner solar system (interior to 3 AU). Open circles are terrestrial planets and planetary embryos. The sizes of the circles scale with the masses. The axes depict semi-major axis and eccentricity of the bodies.

The top panel depicts the initial conditions. The second panel from the top, at $t = 70$ kyr depicts Jupiter having migrated to approximately 2 AU. Note that the mass in the inner Solar System is squeezed together by the migration of Jupiter, as some of the planetesimals interior to the planet will move with it. Also note that some of the planetesimals in the inner Solar System are blue because they were scattered by Jupiter and Saturn. In other words, in the Grand Tack scenario water delivery to the terrestrial planets is a generic outcome. I shall

Fig. 6 Growth and migration of the giant planets in a gas disc during the Grand Tack scenario. Taken from Walsh et al. (2011)

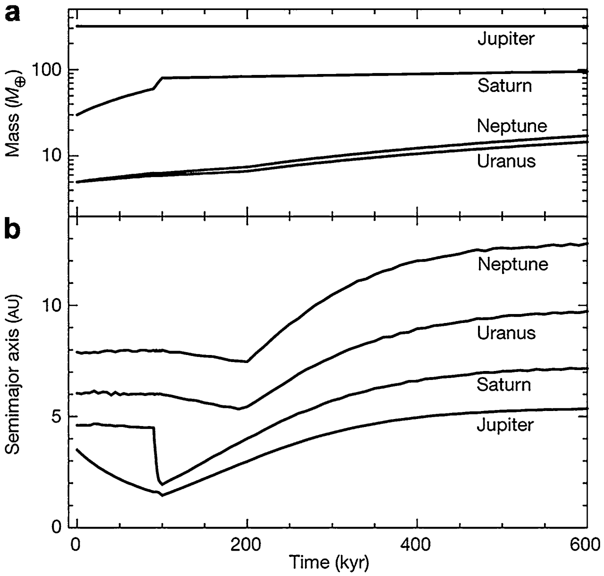
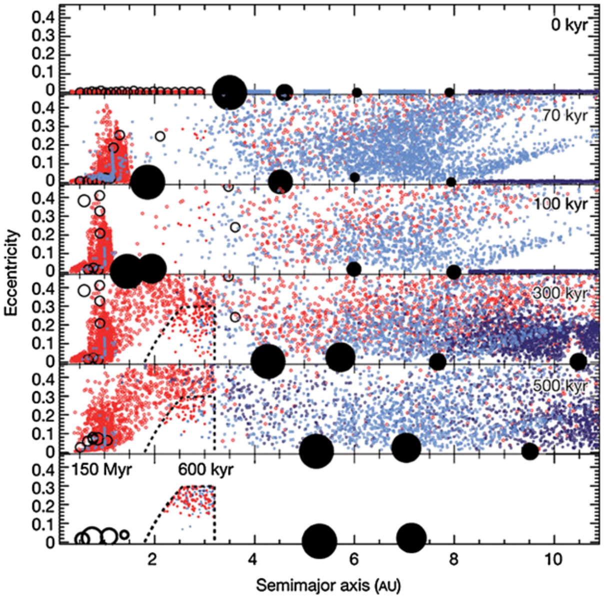


Fig. 7 Migration of the giant planets in a gas disc during the Grand Tack scenario and the evolution of the asteroid belt and inner solar system. Taken from Walsh et al. (2011)



return to this issue later. In the third panel, at $t = 100$ kyr, Jupiter and Saturn are about to reverse their migration. Now the outer Solar System is also filled with red dots, so that a radial mixing of material occurs through the gravitational scattering by Jupiter and Saturn as they migrate through the gas disc. The next two panels depict further outward migration of Jupiter and Saturn. Most of the red dots that originated in the inner solar system form the terrestrial planets and the blue dots that originate in the outer solar system are ejected by the giant planets. Eventually, in the bottom panel, we are left with an asteroid belt, consisting

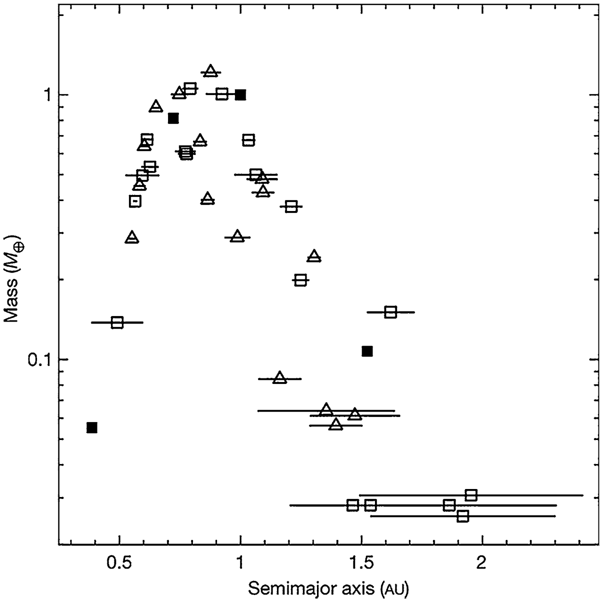


Fig. 8 Masses vs semi-major axis of the simulated terrestrial planets in the Grand Tack scenario. Taken from Walsh et al. (2011)

of both blue and red dots, and the terrestrial planets 150 Myr later. The radial mixing in the asteroid belt is a possible explanation to the compositional gradient of the asteroid belt.

After this short overview of the Grand Tack scenario, I shall turn to the formation of the terrestrial planets.

4.1 Terrestrial Planet Formation During the Grand Tack Scenario

The formation of the terrestrial planets in the Grand Tack scenario proceeds in a similar manner to that described in Hansen (2009). In Fig. 8 I depict the masses of the planets that were formed in several simulations from Walsh et al. (2011) as a function of their semi-major axis. This figure should be compared with Fig. 3, taken from Hansen (2009). The filled squares correspond to the current terrestrial planets. The triangles and squares correspond to simulations with different starting conditions, but the outcome tends to be the same: the masses of the terrestrial planets are well reproduced, which is no surprise because the model basically reproduced the initial conditions of Hansen (2009). Once again, the small mass of Mars is also reproduced, which was the aim of the model, and Mercury and Mars are more inclined and eccentric than Earth and Venus.

I showed above that the Grand Tack scenario brought water to the terrestrial planets. The estimation of the water delivery to the terrestrial planets in the Grand Tack scenario is an ongoing study, but I will present some preliminary results here, based on the work of O'Brien et al. (2010). Table 1 shows the mass, orbital elements and fractional make up of Mars-sized planets from several of the simulations presented in Walsh et al. (2011) and O'Brien et al. (2010). There are several interesting trends. First of all, the majority of the mass of the Mars-sized analogues consist of material from embryos rather than planetesimals, with all cases being formed from a single embryo that accreted some planetesimals. If these simulations are representative of the formation of Mars then it suggests that Mars is a leftover planetary embryo. Second, the orbital elements are more or less consistent with the current orbit of Mars. The last two embryos seem to have most

Table 1 This table shows the mass, fraction of mass from embryos, semi-major axis, eccentricity and inclination of Mars analogues formed in a few of the Grand Tack simulations of Walsh et al. (2011). The remaining columns show, in percent, the fraction of material that originated from the various regions

M ($M_\oplus$)	Frac. emb. (%)	a (AU)	e	i (°)	< 1	1–1.5	1.5–2	2–3	> 3
0.06	82.3	1.50	0.03	11.7	0.0	4.1	86.4	4.1	5.4
0.05	96.2	1.67	0.08	5.1	0.0	0.0	0.0	96.2	3.8
0.07	78.4	1.38	0.07	5.1	3.9	11.8	0.0	82.3	2.1

of their material come from between 2 AU and 3 AU while the first one has most of its material from between 1.5 AU and 2 AU, suggesting that the real Mars is most likely a mixture of both. In terms of water content, if I naively assume that only material beyond 3 AU has a water content (Morbidelli et al. 2000), and when pegging this at 5 % by mass (Morbidelli et al. 2000), then the putative Mars should have approximately 0.1–0.2 % by mass in water. This is most likely an upper limit and carries a large uncertainty, and thus it should only be used as a guidance rather than absolute. In comparison, for the Earth this value is approximately 0.05 % to 0.1 % (Morbidelli et al. 2000; Murakami et al. 2002). In any case, it suggests that Mars, shortly after its formation, could have carried a substantial amount of water. However, whether it could retain it remains to be seen. In any case, while the final outcome in terms of planet semi-major axis and mass in the Grand Tack scenario is very similar to that of Hansen (2009), there is a large difference in the final outcome in terms of planetary composition: Hansen's planets are dry while the Grand Tack planets have a certain percentage of icy material from beyond the snow line.

It appears that Grand Tack scenario can sculpt the disc from which the terrestrial planets form to a small enough size to reproduce Hansen's (2009) initial conditions, and to account for the water content of the Earth. The next question then is whether or not the Grand Tack scenario is compatible with cosmochemical constraints. This is discussed in the next section, focusing on Mars.

5 Comparison with Cosmochemical Constraints

In this section the formation of Mars in the Grand Tack scenario is compared with cosmochemical constraints. Hansen (2009) already discussed some of this when applied to all of the terrestrial planets, and showed that the growth of Mars occurs on a time scale less than 10 Myr (see Fig. 4 above). This growth time scale is consistent with the cosmochemical evidence presented in Nimmo and Kleine (2007), who suggested a Martian formation time between 1 Myr to 10 Myr. In addition, the Grand Tack scenario suggests that the composition of Mars consists of a mixture of materials whose origin span several AU in range, consistent with findings by Lodders (2000). The short formation time scale based on cosmochemical evidence, the small mass of Mars and the results from the formation simulations in the Grand Tack scenario suggest that Mars is a left-over embryo rather than a fully-formed planet. Is this indeed the case?

The best, most recent evidence that Mars is actually a planetary embryo comes from Dauphas and Pourmand (2011). They analyse the 182 Hafnium-Tungsten (^{182}Hf-^{182}W) decay system in the shergottite-nakhlite-chassignite (SNC) meteorites and improve on the currently-known values by analysing the Th/Hf and ^{176}Hf/^{177}Hf ratios in chondrites that reflect remobilisation of Lutetium and Thorium during parent-body processes. The excess abundance of ^{182}W, produced from the radioactive decay of ^{182}Hf, relative to other non-radiogenic isotopes in the Martian mantle, can be used to determine the age of core formation of Mars. See also the chapter by Metzger et al. (Core Formation and Mantle Differentiation on Mars).

During oligarchic growth of protoplanets the mass of the planet can be approximated as $M(t) = M_{\mathrm{Mars}} \tanh^3(t/\tau)$ (Chambers 2006). The value of τ is the accretion time scale. Dauphas and Pourmand (2011) use the excess abundance of ^{182}W in the Martian mantle, the decay of ^{182}Hf, the Hf/W ratios and the typical composition of a chronditic uniform reservoir to compute $\tau = 1.8^{+0.9}_{-1.0}$ Myr. They argue this is a robust upper limit. Thus, most of the Martian accretion took place during the first 4 Myr of the Solar System, even before dissipation of the solar nebula. This time scale is in excellent agreement with the findings of Hansen (2009) and suggests that Mars is indeed a left-over planetary embryo. It is worthy to note that Mars had gained almost its full size while in parts of the disc closer to the Sun planets were still forming, based on the fact that chondrites formed $\gtrsim 3$ Myr after CAIs (Kleine et al. 2009). The idea that Mars is an embryo may also explain the similarities between its atmosphere and that of the Earth because both show isotopically fractionated Xenon (Pepin 1991). The Earth may have inherited the fractionated Xe from the atmosphere of a Mars-sized embryo that collided with it and formed the Moon.

6 Summary and Conclusions

In this chapter I have given an overview of the latest models of terrestrial planet formation, and focused on Mars in particular. The small mass of Mars has been a long-standing problem in terrestrial planet formation because it is very difficult to reproduce in numerical simulations. Indeed, planets at the position of Mars were always a factor of a few too massive.

A breakthrough in this long-standing problem came when Hansen (2009) considered terrestrial planet formation from a narrow annulus of material between 0.7 AU and 1 AU. Hansen noted that Mars finished growing within 10 Myr and from the dynamics suggested that Mars was a protoplanet that got scattered outwards and accreted no additional material. While the coagulation of material from this ring was able to reproduce the current terrestrial system very nicely, it had two shortcomings: the material was dry and there was no physical explanation to truncate the disc at 1 AU. Several reasons were proposed but the most recent one was a dynamical sculpting by the migration of Jupiter and Saturn in the gas disc, called the Grand Tack scenario. This migration could truncate the disc at 1 AU and reproduce the initial conditions of Hansen (2009). The model has the advantage that water-rich material from the outer Solar System got mixed with the water-poor material from the inner Solar System, thereby accounting for the water on Earth and the other terrestrial planets. From this model it is expected that Mars contains up to 0.2 % of water by mass.

When analysing the growth of Mars in the Grand Tack scenario, it appears that Mars is a left-over protoplanet that got stranded outside the main disc of material and stopped growing after a few million years. A recent study by Dauphas and Pourmand (2011), based on Thorium/Tungsten and Thorium/Hafnium ratios in the Martian mantle, confirm that the growth time of Mars was of the order of 2 Myr, well within the upper limit of 10 Myr suggested by Hansen (2009) and once again confirming that Mars is a remnant planetary embryo.

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