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The formation of Jupiter by hybrid pebble–planetesimal accretion

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The standard model for giant planet formation is based on the accretion of solids by a growing planetary embryo, followed by rapid gas accretion once the planet exceeds a so-called critical mass[1]. However, the dominant size of the accreted solids ('pebbles' of the order of centimetres or 'planetesimals' of the order of kilometres to hundreds of kilometres) is unknown[1,2]. Recently, high-precision measurements of isotopes in meteorites have provided evidence for the existence of two reservoirs of small bodies in the early Solar System[3]. These reservoirs remained separated from ~1 Myr until ~3 Myr after the Solar System started to form. This separation is interpreted as resulting from Jupiter growing and becoming a barrier for material transport. In this framework, Jupiter reached ~20 Earth masses ($M_\oplus$) within ~1 Myr and slowly grew to ~50 $M_\oplus$ in the subsequent 2 Myr before reaching its present-day mass[3]. The evidence that Jupiter's growth slowed after reaching 20 $M_\oplus$ for at least 2 Myr is puzzling because a planet of this mass is expected to trigger fast runaway gas accretion[4,5]. Here, we use theoretical models to describe the conditions allowing for such a slow accretion and show that Jupiter grew in three distinct phases. First, rapid pebble accretion supplied the major part of Jupiter's core mass. Second, slow planetesimal accretion provided the energy required to hinder runaway gas accretion during the 2 Myr. Third, runaway gas accretion proceeded. Both pebbles and planetesimals therefore play an important role in Jupiter's formation.

High-precision measurements of isotopes (molybdenum, tungsten and platinum) in meteorites have recently been used to temporally and spatially constrain the early Solar System[3], by combining two main cosmochemical observations (see Methods). On the basis of these data, the existence of two main reservoirs of small bodies in the early Solar System can be inferred[6–8]. These reservoirs remained well separated for about 2 Myr because of the formation of Jupiter and were reconnected only when the planet grew massive enough to scatter material from beyond Jupiter's orbit to inner regions of the Solar System[3]. This cosmochemical evidence, which has never been included in growth models of Jupiter, places severe constraints on planet formation models.

We simulate Jupiter's growth at its present location by solid and gas accretion by using state-of-the-art planet formation models[9] to determine the time required for Jupiter to reach 50 $M_\oplus$, the mass presumably needed to reconnect the two reservoirs[3]. We checked, using N-body simulation, that this mass is indeed large enough for efficient scattering to happen (see Supplementary Information). We consider different values for the mass of Jupiter at 1 Myr and for the average accretion rate of solids after 1 Myr. As the opacity and the composition of Jupiter's envelope are not precisely known, we ran models using a large range of assumptions (low or high opacity, pure hydrogen and helium, or envelope enriched in heavier elements). The model results show that the cosmochemical constraints are met, but only with a planetary mass at 1 Myr between about 5 $M_\oplus$ and 16 $M_\oplus$ depending on the assumed conditions (Fig. 1). Therefore, the minimum mass of the forming Jupiter that is required to prevent the transport of pebbles (the 'pebble isolation mass') is somehow smaller than the 20 $M_\oplus$ inferred previously[3]. Note that the precise values of the pebble isolation mass and the mass that Jupiter should have attained at about 3 Myr after the beginning of the Solar System are not directly derived from cosmochemical studies, but result from theoretical interpretation[3].

Our models also show that a relatively high solid accretion rate (at least $10^{-6}\,M_\oplus\,\mathrm{yr}^{-1}$) is required to prevent rapid gas accretion after 1 Myr. Indeed, slow gas accretion is possible only through substantial thermal support of the gas-dominated envelope that can counteract the strong gravity of the planetary core. We find that the dissipation of the kinetic energy from infalling solids thermally supports the envelope and inhibits high gas accretion rates. We checked that the ranges of values of pebble isolation mass and solid accretion rates are very robust and insensitive to the envelope composition and/or the opacity values, the planet's location and the disk properties (see Supplementary Figs. 1 and 2).

Because Jupiter reached the pebble isolation mass around 1 Myr, maintaining a high solid accretion rate after this time must result from the accretion of planetesimals, which do not experience the isolating effect of the planet as pebbles do (see Supplementary Information). During the first million years, the solid accretion rate needs to be as high as about $10^{-5}\,M_\oplus\,\mathrm{yr}^{-1}$ for Jupiter to reach a mass of about 5–16 $M_\oplus$ in only 1 Myr. This accretion rate is too high to result from the accretion of planetesimals and must result from the accretion of pebbles (see Supplementary Information). However, a rate of at least $10^{-6}\,M_\oplus\,\mathrm{yr}^{-1}$ in planetesimal accretion is required to stall runaway gas accretion and keep the planetary mass below 50 $M_\oplus$ for the next 2 Myr. Hence, fulfilling the cosmochemical time constraints[3] in a Jupiter formation scenario is possible only through a hybrid accretion process where, first, pebbles provide high accretion rates and grow a large core (about 5–16 $M_\oplus$) and, second, substantial planetesimal accretion sets in afterwards. This planetesimal accretion, which occurs after 1 Myr, supplies the energy required for delaying rapid gas accretion and only modestly contributes to the core's mass.

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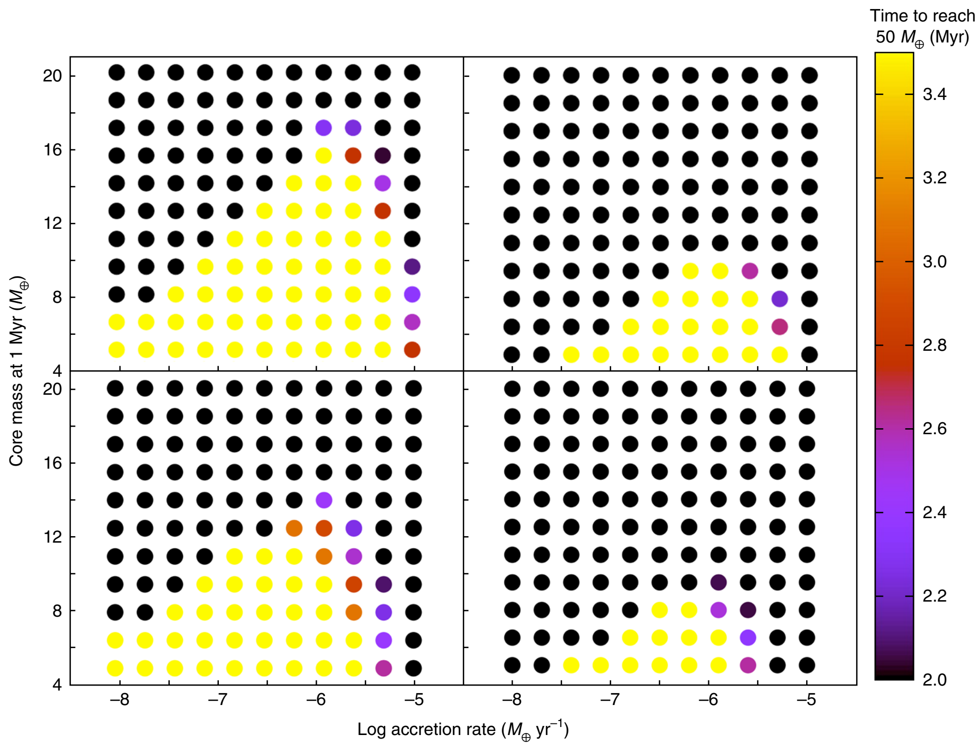

Fig. 1 | Time to reach 50 $M_\oplus$ as a function of the core mass at 1 Myr and the solid accretion rate ($M_\oplus$ yr^{-1}, log scale). Upper left: non-enriched envelope and ISM opacity[39]. Upper right: non-enriched envelope and opacity reduced by a factor of ten compared with the ISM value. Lower left: enriched envelope and ISM opacity. Lower right: enriched envelope and reduced opacity. The yellow region delimits where the core growth is too slow; the black region delimits where the runaway gas accretion occurs too early (because either the initial core mass is too large or the heating by incoming planetesimals is too small). Colours between purple and orange indicate the region that is compatible with the growth timescale of Jupiter as obtained from cosmochemical studies[3]. Note that in all cases, the parameter space that is consistent with the cosmochemical constraints[3] is small.

The derived accretion rate of planetesimals onto Jupiter represents a substantial flux of infalling solids. Such high accretion rates cannot be sustained by large (hundreds of kilometres in size) planetesimals, given the excitation they experience from the gravitational interaction with a growing planetary embryo and the inability of gas drag to damp the eccentricity and inclination of such big objects[10,11]. Thus, our results suggest that a substantial mass of small planetesimals (kilometres in size) was present in the solar nebula at 1 Myr (see Fig. 2 and Supplementary Information), in apparent contradiction to recent studies suggesting the existence of large primordial planetesimals[12,13]. These smaller objects would, therefore, be second-generation planetesimals, resulting from the fragmentation of larger primordial objects[14]. Indeed, the presence of a planet of a few Earth masses leads to collisions that are violent enough to disrupt primordial planetesimals[14]. Moreover, the collision timescale among large planetesimals is short enough to allow the formation of small ones by fragmentation in less than 1 Myr (see Supplementary Information). In this way, the initial growth of Jupiter by pebble accretion during the first million years provided the conditions to fragment large primordial planetesimals into small second-generation objects in a timely manner.

Our formation scenario also provides a solution to the problem of the timing of pebble accretion. Indeed, pebble accretion is so efficient that objects quickly become more massive than Jupiter unless accretion starts shortly before the dispersal of the protoplanetary disk[15,16]. This timing is inconsistent with detailed models of pebble growth, which conclude that pebbles form and accrete early[17]. In the hybrid pebble–planetesimal scenario, the formation of Jupiter-mass planets is stretched over a few million years, comparable to the typical lifetimes of circumstellar disks[18]. In this case, it is possible that pebbles are accreted in the early phases of protoplanetary disk evolution, without leading necessarily to the formation of massive planets.

We conclude that Jupiter formed in a three-step process (Fig. 3). (1) Jupiter's core grew by pebble accretion. The contribution of large primordial planetesimals to the solid accretion was negligible. As Jupiter's core became more massive, large primordial planetesimals dynamically heated, collided and formed second-generation smaller planetesimals. (2) Pebble accretion ceased (Jupiter reached the pebble isolation mass), and the protoplanet grew more slowly by the accretion of small planetesimals. The solid accretion rate remained high enough to provide sufficient thermal support to the gas envelope and to prevent rapid gas accretion. (3) The critical mass for gas accretion was reached, gas rapidly accreted and Jupiter reached its present-day mass. During this last phase, further solids may have been accreted, increasing the final heavy-element content in Jupiter[19].

Our simulations show that the total heavy-element mass in Jupiter (core and envelope) before runaway gas accretion (accounting for both pebble and planetesimal accretion) ranges from 6 $M_\oplus$ to 20 $M_\oplus$. These values can be compared with Jupiter's heavy-element mass as derived from structure models, which ranges from 23.6 $M_\oplus$ to 46.2 $M_\oplus$ (ref. [20]). This comparison implies that Jupiter accreted up to about 25 $M_\oplus$ during runaway gas accretion or at a later stage[19]. Heavy elements that accreted late do not necessarily reach the core. They can dissolve in the envelope[21], leading to envelope enrichment and the formation of heavy-element gradients[22].

In this new hybrid pebble–planetesimal scenario, the time a protoplanet spends in the mass range of 15–50 $M_\oplus$ extends over a few million years before rapid gas accretion takes place. Because the

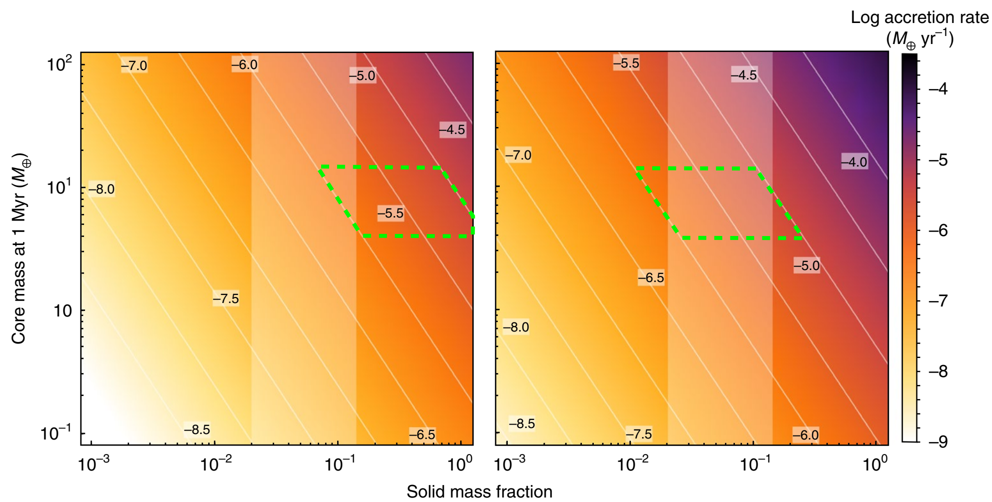

Fig. 2 | Accretion rate of planetesimals as a function of the solid mass fraction and the core mass at 1 Myr. Left: large planetesimals (100 km in size). Right: small planetesimals (1 km in size). The green dashed regions delimit the parameters that allow the cosmochemical constraints[3] (core mass of ~5–16 $M_\oplus$ and solid accretion rate of 10^{-6}–10^{-5} $M_\oplus$ yr^{-1}) to be matched. The vertical pale shaded bands delimit the likely solid mass fraction according to the standard minimum-mass solar nebula model for the lowest value[40] and the dust-to-planetesimal formation models for the highest value[41]. Values next to diagonal white lines indicate the log accretion rate ($M_\oplus$ yr^{-1}).

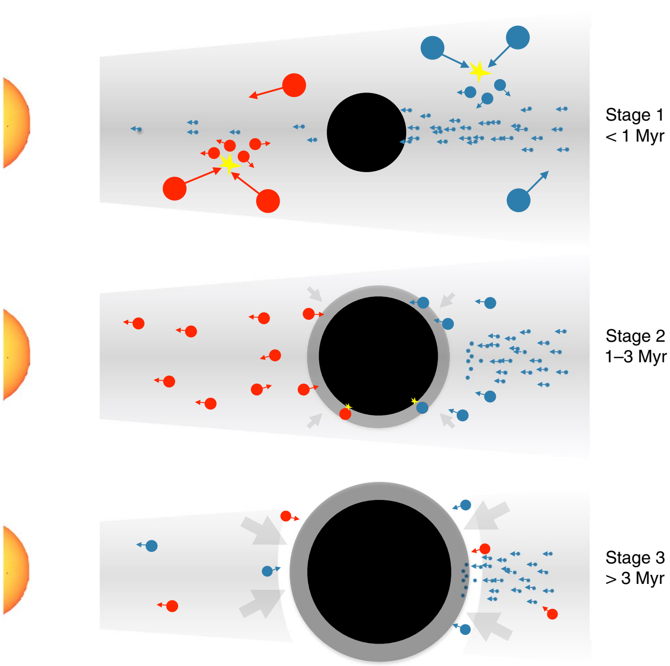

Fig. 3 | The three stages of the hybrid pebble–planetesimal formation model. Stage 1 (up to 1 Myr): Jupiter (black) grows by pebble accretion (small circles), and planetesimal accretion is negligible. Large primordial planetesimals (large circles) are excited by the growing planet and suffer high collision velocities (large arrows), leading to destructive collisions (yellow), which produce small, second-generation planetesimals (medium circles). Stage 2 (1–3 Myr): Jupiter is massive enough to prevent pebble accretion. The energy associated with the accretion of small planetesimals is large enough to prevent rapid gas accretion (grey arrows). Stage 3 (after 3 Myr): Jupiter is massive enough to accrete large amounts of gas (hydrogen, helium). Nearby pebbles and small planetesimals can be gravitationally captured. Ultimately, a gap (white) is opened in the solar nebula, stopping further gas accretion. Red and blue indicate the two reservoirs of small bodies (inside and outside Jupiter's orbit, respectively), which are separated by Jupiter's growth in stage 2 and reconnected in stage 3. The Sun is shown on the left.

final mass of a planet is determined by the dissipation of the protoplanetary disk, our formation scenario increases the likelihood of forming intermediate-mass planets, which provides a natural explanation for the formation of Uranus and Neptune[1,23].

Methods

Meteoritic constraints. Kruijer et al.[3] constrained Jupiter's growth history by combining two main cosmochemical observations. First, cosmochemical data of the youngest inclusions (chondrules) in primitive meteorites constrain the maximum accretion age for small primitive bodies, while the short-lived ^{182}Hf to ^{182}W decay system dates metal–silicate separation and, as such, the accretion timescales of small differentiated bodies and planets. Second, distinct nucleosynthetic isotope compositions (for example, of molybdenum or tungsten) that were imprinted in dust accreted by planetary bodies allow regions in the protoplanetary disk with originally distinct dust compositions to be identified. On the basis of this, cosmochemical data constrain two main reservoirs of small bodies that existed in the early Solar System[6–8]. They remained well separated for about 2–4 Myr (refs [3,24]). The separation of these two reservoirs occurred in the first million years after the beginning of the Solar System, as defined by the formation of the oldest Solar System materials (Ca–Al-rich inclusions). It was proposed[3] that this separation was initiated by the growth of proto-Jupiter reaching pebble isolation mass (20 $M_\oplus$), thereby isolating the population of pebbles inside and outside its orbit. The two reservoirs remained separated until Jupiter grew massive enough to scatter small bodies, reconnecting the reservoirs. This occurred when Jupiter reached 50 $M_\oplus$, and not earlier than 3–4 Myr after Ca–Al-rich inclusion formation[3]. While cosmochemical evidence constrains the timescale of the separation of the reservoirs, it does not constrain the mass that Jupiter had at these epochs.

Modelling planetary growth. We compute planetary growth in the framework of the core accretion model by solving the planetary internal structure equations[4,5], assuming that the luminosity results from the accretion of solids and gas contraction.

We consider two limiting cases regarding the fate of solids accreted by proto-Jupiter. In the first case, the so-called non-enriched case, all the accreted heavy elements are assumed to sink to the centre (core). In this case, the envelope is made of pure H and He. In the second case, the enriched case, we assume that the volatile fraction of the accreted solids is deposited in the envelope, whereas the refractory component reaches the core[20,25]. The volatile fraction is assumed to be 50 wt%, following recent condensation models[26]. The luminosity in this case is that provided by the refractory material only, since the volatiles are assumed to remain mixed in the envelope and contribute to the luminosity generated by its contraction[25]. In all the models presented here, we treat the accretion rate of solids between 1 Myr and 3 Myr as a free parameter that varies from 10^{-8} $M_\oplus$ yr^{-1} to 10^{-5} $M_\oplus$ yr^{-1}.

The internal structure equations[4,5] are solved by using, as boundary conditions, the pressure and temperature in the protoplanetary disk at the position of the planetary embryo, and by defining the planetary radius as a combination of the

Hill and Bondi radii[27]. The evolution of the planetary envelope depends on the equation of state and opacity used. For the non-enriched case, we use the equation of state of H and He (ref. [28]). For the enriched case, the envelope is assumed to be composed of H, He and water, and we take into account the mixture of the three components[25,28,29]. For the opacity, we use either interstellar medium (ISM) opacity[39], or a reduced opacity in which we multiply the ISM opacity by 1/10 to mimic the possible opacity reduction due to grain growth[30,31]. The calculations do not include the effect of destruction and replenishment of pebbles in Jupiter's envelope[32,33], because the growth of Jupiter after 1 Myr is dominated by the accretion of planetesimals, for which the effect of destruction in the planetary envelope is less important[33].

Disk structure. The disk model provides the pressure and temperature at the location of Jupiter's formation, which serve as boundary conditions for computation of the internal structure. This model is designed to fit two-dimensional radiative hydrodynamic simulations of protoplanetary disks[34].

Planetesimal accretion. In early planet formation models, it was assumed that the accreted solids were large planetesimals[4] (hundreds of kilometres in size), in agreement with several theoretical and observational constraints[12,13]. These planetesimal-based formation models still face the problem that the time required to reach rapid gas accretion is comparable to or even longer than the disk's lifetime[4,18]. This challenge is even more severe if dynamic heating (increased eccentricity and inclination) of the planetesimals by the gravity of a proto-Jupiter is considered[10,35] (see also Supplementary Information), because this hinders the core growth. Dynamic heating is counteracted by damping caused by gas drag and thus primarily affects small planetesimals. Hence, accreting solids that are only a few kilometres in size can relieve the timescale problem[9,10]. Numerical simulations, however, predict much larger typical sizes for primordial planetesimals, of the order of tens to hundreds of kilometres[12], with most of the mass stored in the largest bodies, in agreement with the constraints from the asteroid belt[13]. Therefore, kilometre-size planetesimals are probably generated by the collisional fragmentation of large primordial planetesimals. This in turn requires high collision velocities, which result from the gravitational stirring of primordial planetesimals by objects of a few Earth masses[14].

Planetesimal accretion depends on three factors: the amount of planetesimals near the planet, the mass of the forming planet and the degree of planetesimal excitation. In particular, the planetesimal accretion rate depends on the gravitational focusing factor, F_{grav}, itself depending inversely on the relative velocity between planetesimals and the growing Jupiter, v_{rel}. When planetesimals are dynamically excited (that is, when they have large eccentricity and inclination), v_{rel} increases, and the planetesimals are accreted less efficiently. Planetesimals are excited by the forming planet and by planetesimal–planetesimal interactions and are damped by gas drag. Large planetesimals are more excited than small ones because gas drag is less active on the former. Therefore, v_{rel} is larger for large planetesimals, leading to smaller accretion rates than for small planetesimals. We compute the accretion rate of planetesimals[14] that are 100 km or 1 km in size as a function of the planetary mass and planetesimal/gas mass ratio. The properties of the gas disk that are required for this calculation (for example, gas density) are taken from the disk model at a radial distance of 5.2 AU and an age of 1 Myr (when planetesimal accretion begins).

Fragmentation of large planetesimals. Two conditions are required to account for the formation of small planetesimals from the fragmentation of large ones before 1 Myr (when the accretion of pebbles stops). Collisions must be both frequent enough (so that small planetesimals are produced rapidly enough) and violent enough (so that collisions lead to fragmentation). We estimate the collision timescale[36,37] between planetesimals that are 100 km in size as a function of the protoplanet's mass and the solid surface density at 5 AU. The collision frequencies are calculated for a single-size population of planetesimals. The calculation includes the stirring of planetesimals by the growing Jupiter, but not the interaction between planetesimals, which is negligible for planets of a few Earth masses[11]. Including this effect would increase the excitation of planetesimals, leading to even more violent collisions and further fragmentation. We also include the gas drag that decreases the eccentricity and inclination of planetesimals and, therefore, their collision velocity. To determine in which case the collisions lead to the destruction of planetesimals, we compared the specific energy of the collision with that required for disruption, Q^*_D. We chose for this value a very conservative estimate of 6×10^9 erg g^{-1}, which corresponds to the highest value found for any set of compositional parameters[38]. As a result, for all collisions involving an energy larger than Q^*_D, planetesimals are expected to be destroyed and to fragment into much smaller objects. More details on the calculation of the fragmentation of large planetesimals are in the Supplementary Information.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Y.A. initiated the project. Y.A., J.V., S.A., R.B. and L.S. performed the theoretical calculations. Y.A., J.V. and R.H. led the writing of the manuscript, and all authors contributed to the discussion and interpretation of the results.

Competing interests

The authors declare no competing interests.

Additional information

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