

EPSC2017
EX3 abstracts

On origin of (any) exoplanetary comet families

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1. Introduction

In the work [1] the transitions of comets from the three dimension heliocentric parabolic orbits into the three dimension heliocentric elliptic orbits in the gravitational fields of the Solar system's planets and the Sun have been considered. Here we investigate the process of (any) resonant comets origin in the exosolar systems in the gravitational fields of exoplanets and in the corresponding stars in the frame of planar pairwise two body problem. We find semi major axes (a') of a cometary orbit, eccentricity (e') of the orbit and angle of deflection θ between the vectors of initial and final velocities of the comet. Assume, a comet with a parabolic orbit ($e_0=1$) approaches in the periastron with a planet and the orbit of the comet rapidly transforms into the star centric elliptical orbit. Let the ratio of the new comet's and the planet's periods is equal to $T_c:T_p=1:n$ and the radius of the circle orbit of the planet equals a . (In this model interaction of the comet and planet gives turn of the vector of the planet centric velocity of the comet V_{cp} in the periastron of the parabolic orbit of the comet. For the initial moment of time the vector of the star centric parabolic velocity of the comet V_c – in the periastron of the comet orbit – is parallel to the vector of the star centric circle velocity V_p of the planet).

2. The base equations

The star centric circle velocity V_p of the planet is determined by the equation (1)

$$V_p = \sqrt{\frac{GM_s}{a}}. \quad (1)$$

The star centric parabolic velocity V_c of the comet is found from the condition (2)

$$V_c^2 = \frac{2GM_s}{a}. \quad (2)$$

The planet centric velocity V_{cp} of the comet for the moment of time of it approaching with the planet equals

$$V_{cp} = V_c - V_p. \quad (3)$$

The star centric velocity of the comet V_c' in the elliptic orbit is equal to

$$V_c'^2 = GM_s \left(\frac{2}{a} - \frac{1}{a'} \right). \quad (4)$$

Here G is gravitational constant, M_s is mass of the star, a' – semi major axes of the cometary star centric elliptical orbit. Using the third law of Kepler's (5)

$$\frac{T_p}{T_c} = \left(\frac{a}{a'} \right)^{3/2}, \quad (5)$$

we have

$$V_c'^2 = \frac{GM_p}{a} (2 - n^{2/3}) \quad (6)$$

In the (Fig. 1.) are presented – V_p is the star centric velocity of the planet, V_{cp} is the planet centric velocity of the comet – (after the comet leaves the gravitational sphere of the planet action), star centric velocity of the comet in the elliptic orbit is V_c' and θ is the angle of deflection of the planet centric velocity of the comet V_{cp} .

V_c' is equal to

$$V_c'^2 = V_p^2 + V_{cp}^2 - 2V_p V_{cp} \cos(180^\circ - \theta). \quad (7)$$

Then

$$\cos \theta = \frac{V_c'^2 - V_p^2 - V_{cp}^2}{2V_p V_{cp}}. \quad (8)$$

So, we find

$$\cos \theta = \frac{\frac{GM_s}{a}(2 - n^{2/3}) - \frac{GM_s}{a} - \frac{GM_s}{a}(\sqrt{2} - 1)^2}{2 \cdot \sqrt{\frac{GM_s}{a}} \cdot \sqrt{\frac{GM_s}{a}} \cdot (\sqrt{2} - 1)}.$$

(9)

Or

$$\cos \theta = 1 - n^{2/3} \cdot (\sqrt{2} + 1) / 2. \quad (10)$$

Moreover, it is easy to show (in our model of the comet motion)

$$2a' = a + a'(1 - e') \quad \text{and} \\ e' = n^{2/3} - 1. \quad (11)$$

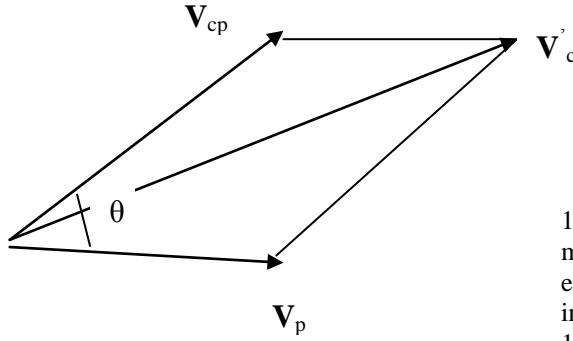


Figure 1: Turning the vector of the planet centric velocity V_{cp} of the comet in the gravitational field of the exoplanet by the angle θ . (See (9)).

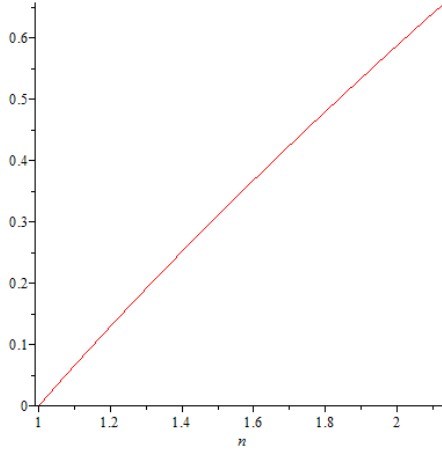


Figure 3: The final eccentricity e' of the elliptical orbit of the exoplanetary comet

depends upon ratio n of planet's and comet's periods (See (11)).

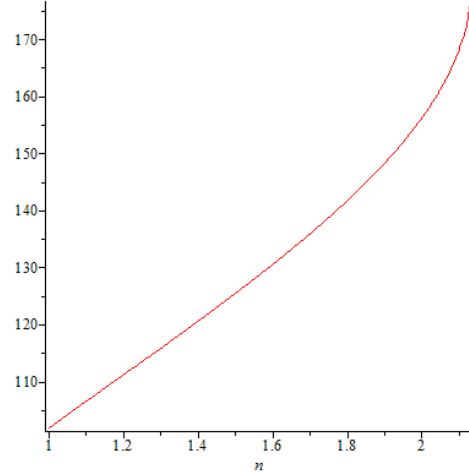


Figure 2: Angle θ depends upon the ratio n of planet's and comet's periods (See (10)).

3. Conclusions

1. In accordance with the proposed celestial mechanical model there are undiscovered comets in exosolar systems of planets. These comets move inside of the orbits of the exoplanets (for $1 < n < 2.132683746$).
2. For $1 < n < 2.132683746$ we have $101.9528559^\circ < \theta < 180^\circ$ (see (10) and (Fig. 2)). $0 < e' < 0.656854250$ (see (11) and (Fig. 3)).
3. Comets with the considered parameters are discovered in the Solar system and they are refeed for the families of Jupiter, Saturn, Uranus and Neptune [1]. Especially we pay attention the case for $n=2$.
4. Of course, the exact models of the comet migration demonstrate – the parameters of the final comet orbit depend on the mass of the star (M_s), the exoplanet mass (M_p), the radius of the exoplanet (R_p), radius of the exoplanet circle orbit (a) and the angle i between the planes of the orbits of the star and the comet [1].

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Gap opening by gas accretion and influence on planet populations

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Abstract

Giant planets grow and migrate in protoplanetary disks. Because they accrete gas from their horseshoe region until the latter is depleted, giant planets can open a gap before being lost into their central star by type I migration. A reduced type II migration is then necessary to limit the total amount of migration that a giant planet suffers during its formation.

1. Introduction

Planets form and migrate in gaseous proto-planetary discs. Giant planets open gaps in the disc above a critical mass M_{gap} of a few hundred Earth masses; then, they follow the slow, so-called type II migration. Below M_{gap} , planets are subject to the fast type I migration, whose timescale is much shorter than the disc lifetime for planets above $\sim 10M_{\oplus}$. Fortunately, the generally inwards type I migration can be directed outwards in some regions of the disk [6], allowing for planets to converge to an equilibrium radius of a few AUs [5]. However, this only works for a limited range of masses, below a critical mass $M_{\text{crit I}} \approx 25 M_{\oplus}$ [1, 4]. The range between ~ 25 and $\sim 100 M_{\oplus}$ therefore appears critical in the growth of a giant planet.

Here, we solve this problem and show [3] (i) that giant planets actually accrete with the runaway growth rate until they open a gap and transition to type II migration (ii) that this accretion rate is fast enough for type I migration to be of limited amplitude between $M_{\text{crit I}}$ and M_{gap} .

We inquire how this better description of the growth and migration of a giant planet affects their final masses and orbital radius. We also explore the role of type II migration, which could be reduced in a so-called dead zone.

2. Gas accretion and gap opening

In most planet population synthesis models, the gas accretion rate of the giant planets does not follow the theoretical runaway growth rates given by 1D or 3D models of a giant planet embedded in a gas disk. Instead, the gas accretion rate of the planet is limited to the gas accretion rate of the disc onto the star. This is rather intuitive: the planet can not accrete more gas than is provided. But this omits that the planet has an easily accessible reservoir of gas to start with: the gas in its horseshoe region. Indeed, as soon as accretion starts, the gas separatrices of the horseshoe region are distorted and the gas next to them is eaten by the planet. The horseshoe region then spreads viscously (fast because it has a small radial extent) into the empty separatrix, where it is funnelled to the planet. Numerical simulations confirm that the accretion rate should not be limited until the horseshoe region is depleted (either by accretion, or by the gravitational torque of the planet). This has two crucial consequences.

2.1. Gas accretion vs type I migration

First of all, as long as the planet has not opened a gap, its accretion rate is the one given by runaway gas accretion models. This rate is proportional to the gas surface density, just like the type I migration rate. Therefore, the race between migration and accretion above $M_{\text{crit I}}$ is fair. Whereas migration wins easily if the gas accretion is limited to the disk supply, we find (both numerically and analytically) that without this limitation, planets open a gap before type I migration makes their orbital radius shrink to zero. In fact the orbital radius is hardly divided by 3 in most cases. In particular, we checked that even a fast migrating planet can open a gap if massive enough; the transition to type II migration then takes about 100 orbits.

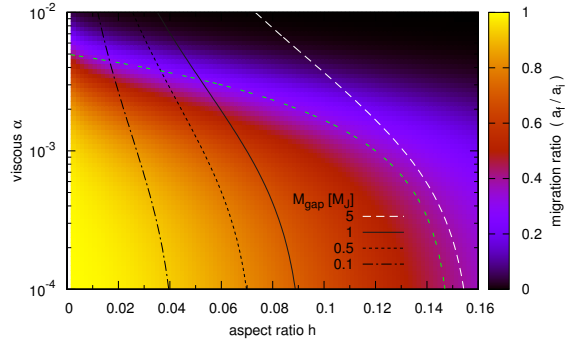


Figure 1: Color map: ratio of the initial to final semi major axis of a planet that migrates in type I migration while growing from 0 to the gap opening mass in the runaway regime. Black and white lines: contours of the gap opening mass M_{gap} . Green double-dashed line: $\alpha = 0.005 - h/30$ (crude proxy for the $a_f/a_i = 0.4$ contour line).

More precisely, figure 1 shows as a color map the ratio of the initial to final orbital radius as a function of the disc parameters (aspect ratio and viscosity), for a planet migrating at the theoretical type I rate while accreting at the theoretical runaway growth rate upto a mass allowing for gap opening.

In summary, above $M_{\text{crit I}}$, planets should migrate inwards fast in type I migration. But if they reached the critical mass to start their runaway gas accretion phase, migration doesn't win over accretion and a gap will be open before the planet is lost. Fortunately, the mass above which the runaway gas accretion start is of the same order as $M_{\text{crit I}}$.

2.2. Final masses & orbits of giant planets

We have modified the planet formation model developed by [2] according to the above description. Specifically, we now compute the amount of gas accreted by the planet, and remove this from the horseshoe region. This region is depleted both by this accretion and by the gravitational torque from the planet. When it is empty, the gas accretion rate of the planet is limited to 80% of the disk supply, and the migration is of pure type II.

As expected, this leads to slightly more massive giant planets, and allows to save giant planets from a fall into their host stars for a wider range of initial conditions. However, most planets still see their orbital radius divided by more than a factor 5 from their birth to their final position. Most of this migration is now coming from the type II phase.

Therefore, we have explored the case of low viscosity disks, mimicking stratified discs with an “active” upper layer and a “dead” midplane. In this case, we expect the type II migration to be very much slowed down. However, the type I migration is always inwards (saturation of the corotation torque); but the dynamical corotation torque [7] limits its amplitude. This allows the total migration of the planets to be limited.

3. Summary and Conclusion

We have studied the competition between gas accretion and migration of growing giant planets. Numerical simulations and analytical calculations show that planets should be able to open a gap before type I migration drives them into their host star.

We have explored the influence of this result on a model of planet formation, and shown its importance. We have further explored the influence of stratified disk model, using a schematic view of the migration in such a disk. Indeed in the layered discs, forming giant planets seem to only experience limited migration and can thus form very close to their final position. These results will be presented.

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Full-lifetime simulations of multiple planets across all phases of stellar evolution

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Based on MNRAS (2016), 458, 3942-3967

Abstract

We know that planetary systems are just as common around white dwarfs as around main-sequence stars. However, self-consistently linking a planetary system across these two phases of stellar evolution through the violent giant branch poses computational challenges, and previous studies restricted architectures to equal-mass planets. Here, we remove this constraint and perform over 450 numerical integrations over a Hubble time (14 Gyr) of packed planetary systems with unequal-mass planets. We characterize the resulting trends as a function of planet order and mass. We find that intrusive radial incursions in the vicinity of the white dwarf become less likely as the dispersion amongst planet masses increases. The orbital meandering which may sustain a sufficiently dynamic environment around a white dwarf to explain observations is more dependent on the presence of terrestrial-mass planets than any variation in planetary mass. Triggering unpacking or instability during the white dwarf phase is comparably easy for systems of unequal-mass planets and systems of equal-mass planets; instabilities during the giant branch phase remain rare and require fine-tuning of initial conditions. We list the key dynamical features of each simulation individually (in [1]) as a potential guide for upcoming discoveries.

1. Introduction

Up until now full-lifetime simulations of multi-planet systems have been restricted to equal-mass planets. Although this assumption significantly helps

constrain the available parameter space to explore, real systems exhibit a variance of planetary masses of a few per cent to many orders of magnitude. Further, previous studies have predominately modelled Jupiter-mass planets, which are rarer than terrestrial planets. Further, no published study has simulated multiple planets with test particles.

Here, we break these barriers, and perform a suite of 14 Gyr simulations of unequal-mass planets, occasionally including test particles, in order to explore the consequences and resulting trends.

2. Figures

Simulations of planetary systems through multiple stages of stellar evolution require both the star and planets to be treated self-consistently as a function of time. We use an existing code which combines planetary (MERCURY) and stellar (SSE) evolution.

The output from SSE was ported directly into a heavily modified version of the MERCURY planetary evolution code. Our version of MERCURY used the Bulirsch–Stoer integrator throughout the simulation, ensuring accurate treatment of potential close encounters. We adopted a tolerance value of 10^{-12} . Stellar mass and radius changes were interpolated within each Bulirsch–Stoer timestep, helping to ensure accuracy. Stars which engulfed planets throughout the course of the simulations had masses which were increased accordingly. Our output frequency was 1 Myr; a shorter frequency would have prohibitively slowed down our simulations. As is the MERCURY default, any collisions between planets were treated as purely inelastic. Further, our

modified code allowed for the tracking of the minimum orbital pericentre of all surviving planets.

Figs. 1-2 illustrate examples of two different full-lifetime simulations, and Fig. 3 illustrates the cumulative statistics for test particles which are engulfed in the white dwarf, across all simulations.

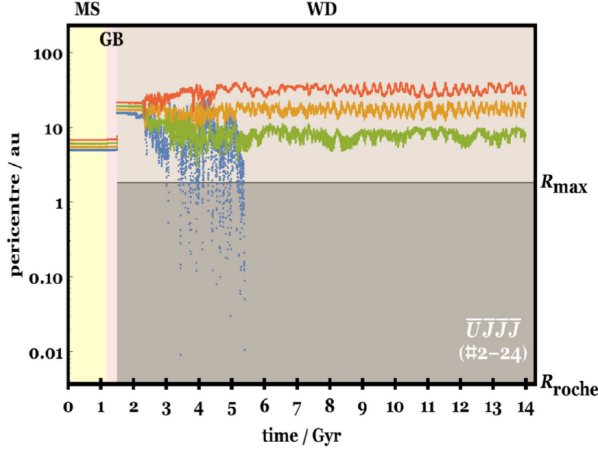


Figure 1: The full-lifetime evolution of four terrestrial planets such that the innermost one is about 5% of the mass of the outer three. The least massive planet is eventually scattered towards the white dwarf.

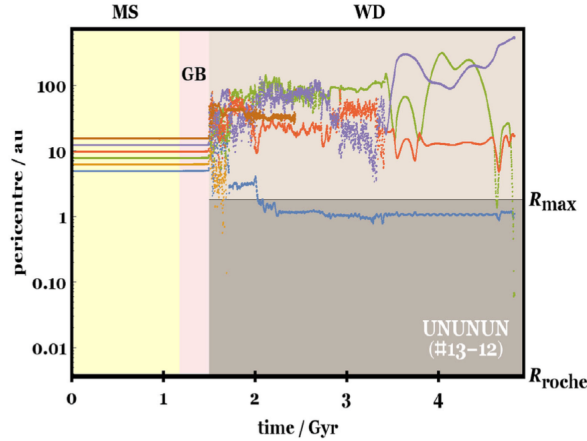


Figure 2: Evolution over 5 Gyr of six planets, three of which are Uranus-mass and three of which are Neptune-mass. Unpacking of the system occurs almost immediately after the giant branch phase.

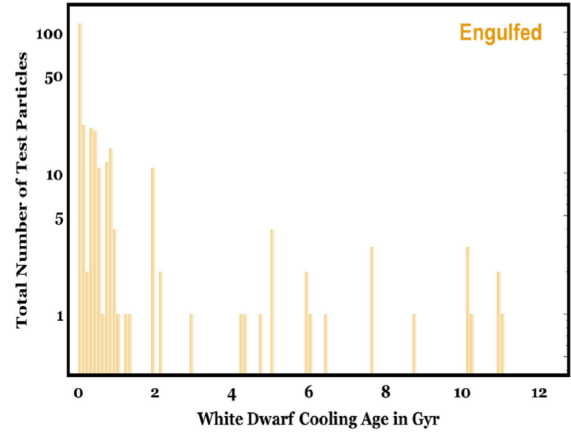


Figure 3: The white dwarf cooling age (time since becoming a white dwarf) at which test particles across all simulations entered the white dwarf Roche, or disruption, radius. The histograms illustrate the pollution decay rate obtained from the simulations.

Acknowledgements

DV and BTG have received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013)/ERC Grant Agreement no. 320964 (WDTracer). AJM acknowledges support from grant number KAW 2012.0150 from the Knut and Alice Wallenberg foundation and the Swedish Research Council (grant 2011-3991).

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Stability of planetary orbits with point of view of the statistical theory of cosmogonical body forming

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Abstract

We derive a unique law called the combined Kepler 3rd law with the universal stellar law connecting thermodynamic parameters of star with orbital characteristics of exoplanets moving around the star. The proposed law explains how the stability of parameters of planetary orbits depends on a constancy of the specific entropy of stellar substance.

1. Introduction

This work investigates the stability of planetary orbits and explains the orbital oscillations [1] in exoplanet systems based on the statistical theory. The statistical theory of a cosmogonical body forming (so-called spheroidal body) has been proposed in [2]–[5]. In particular, the equation of state of an ideal stellar substance based on conception of gravitating spheroidal body has been derived in the paper [5]. Using this equation the universal stellar law (USL) for exoplanetary systems has been obtained [5]. In this work, we show that knowledge of some orbital characteristics of multi-planet extrasolar systems refines the knowledge of the parameters of the stars based on the combined Kepler 3rd law with the universal stellar law (3KL-USL). The proposed 3KL-USL explains how the stability of parameters of planetary orbits depends on constancy of the specific entropy (in conformity with the principles of self-organization in complex systems [6]).

2. The universal stellar law

When the statistical theory of gravitating spheroidal bodies [1-3] is applying to stars we should take into account an extended substance called the stellar corona [5]. In this case, the parameter of gravitational compression α of a spheroidal body [2]–[4] describing the star (in particular, Sun) must be estimated on the basis of linear size of its disk

plus thickness of a visible part of the stellar corona. Within framework of the conception of gravitating spheroidal body, the universal stellar law (USL) connecting temperature, size and mass of each star has been obtained [5]:

$$\sqrt{\alpha} \cdot \frac{\bar{\mu}_r}{i} \cdot \frac{m_p \cdot M}{T} = \kappa, \quad (1)$$

where α is a parameter of gravitational condensation, M and T are stellar mass and temperature respectively, i is a mean number of freedom degree of a moving particle in the highly ionized stellar substance, $\bar{\mu}_r$ is its mean relative molecular weight, m_p is the mass of proton, and κ is the introduced universal stellar constant [5]:

$$\kappa = 3\sqrt{\pi} \cdot \frac{k_B}{\gamma} \approx 1.10003963 \cdot 10^{-12} (\text{kg}^2 / \text{K} \cdot \text{m}), \quad (2)$$

where k_B and γ are constants of Boltzmann and Newton respectively.

Obviously, a verification of USL (1) for different stars requires estimating their parameters $\sqrt{\alpha}$, M , T and also $\bar{\mu}_r$, i.e. chemical composition of stars. By calculating the left part of Eq. (1) for Sun and comparing with the universal stellar constant κ we find coincidence up to the relative error equal $\delta = 3.37\%$ only. To verify the USL for other stars we need approximation of stellar corona temperature T_{cor} through the effective temperature T_{eff} of stellar surface of these stars, i.e. a modification of the USL. This modified USL can be testified by calculating the left part of Eq. (1) with usage of parameters for the different types of stars [5]. First of all, we can note the satisfiability of Eq. (1) for the stars belonging to the spectral class G like Sun: namely, the modified USL is carried out with the small relative accuracy $\delta = 1.34\%$ for the star Kepler-20 of type G8 or $\delta = -0.1\%$ for HD10180 of type G1V. However, the

modified USL is carried out with $\delta = -15.87\%$ for the star α Centauri of type K1V. Thus, the low accuracy of this law for the stars belonging to the spectral classes A or M, most likely, can be explained by too rough approximation T_{cor} for the more bright or dim stars [5].

3. The derivation of the combined Kepler 3rd law with the universal stellar law and explanation of stability of planetary orbits

Now with aim to answer the main question on how a stable level of the gravitational potential is supported around a star in exoplanet system and how owing to it the stability of planetary orbits occurs, let us consider jointly the USL (1) and Kepler 3rd law (3KL):

$$\frac{a^3}{T_K^2} = \frac{\gamma M}{4\pi^2}, \quad (3)$$

where a is a major semi-axis of a planetary orbit, T_K is a Keplerian period of motion of a planet around its star (belonging to our Solar or exoplanet system). Taking into account the formula (2) let us rewrite the USL (1) in the following way:

$$\sqrt{\frac{\pi}{\alpha}} \cdot \frac{3\bar{i}}{m_p \bar{\mu}_r} \cdot k_B T = \gamma M. \quad (4)$$

Then substituting the left part of (4) to the right part of Eq. (3) we obtain the *combined Kepler 3rd law with the universal stellar law* (3KL-USL):

$$\frac{a^3}{T_K^2} = \frac{3k_B}{4\pi^{3/2} m_p} \cdot \frac{\bar{i}}{\bar{\mu}_r} \cdot \frac{T}{\sqrt{\alpha}}. \quad (5)$$

The combined law (5) shows that the stability of parameters of moving planet in orbit is determined by constancy of the value:

$$\frac{\bar{i}}{\bar{\mu}_r} \cdot \frac{T}{\sqrt{\alpha}} = \text{const}. \quad (6)$$

Introducing an angular velocity $\Omega_K = 2\pi/T_K$ of rotation of a planet around star the combined law (5) can be written in the following form:

$$a^3 \Omega_K^2 = s \cdot \frac{\bar{i}}{\bar{\mu}_r} \cdot \frac{T}{\sqrt{\alpha}}, \quad (7)$$

where

$$s = 3\sqrt{\pi} \cdot \frac{k_B}{m_p} \quad (8)$$

is a constant equal $s \approx 4.3890297 \cdot 10^4 \text{ (J/kg} \cdot \text{K)}$.

Let us note that this constant has physical measure of a specific heat capacity c_V or a specific entropy s , i.e. according to Eqs. (7), (8) the stability of parameters of planetary orbits is determined by a *constancy of the specific entropy s* in conformity with the principles of self-organization in complex systems [6]. Really, the constant s can be represented as the following:

$$s = 3\sqrt{\pi} \cdot \frac{k_B}{m_p} \cdot N_A = \frac{3\Re}{2} \cdot \frac{2\sqrt{\pi}}{m_p} = c_{\mu V}^{(1)} \cdot \frac{2\sqrt{\pi}}{m_p}, \quad (9)$$

where $c_{\mu V}^{(1)}$ is a molar heat capacity of one-atomic gas as stellar substance (under the condition of its constant volume V), N_A is Avogadro constant, \Re is the universal gaseous constant.

The combined law connects the mechanical values in the left part of Eq. (7) and the statistical (thermodynamic) values in the right part of this Eq.(7). It means that a stability of the mechanical values (including Ω_K and a) depends on a statistical regularity of the right part of Eq.(7). Thus, we conclude about a presence of *statistical oscillations* of motion of planets and satellites around stars. This conclusion is completely confirmed by existing the radial and the axial orbital oscillations of planets for the first time described by Alfvén and Arrhenius [1].

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Migration of icy objects to forming terrestrial planets

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Abstract

Migration is an important process of matter transport in the solar system. We studied migration of bodies and dust to the terrestrial planets from the regions beyond the snowline and estimated delivery of water and volatiles to these planets. It was found that during the growth of Earth's embryo up to a half of its present mass, the mass of water received by the embryo from the feeding zone of Jupiter and Saturn could amount to about 30% of the total mass of water delivered to the Earth from this feeding zone.

1. Introduction

Water and volatiles could be delivered to the terrestrial planets from different distances from the Sun. It is often supposed [1] that the outer asteroid belt was the main source of the delivery of water to the terrestrial planets. Drake and Campins [2] argued against an asteroids' source of Earth's water because oxygen isotopic composition in its primitive upper mantle matches that of anhydrous ordinary chondrites, rather than hydrous carbonaceous chondrites. Hallis [3] noted that the deep mantle water has a low D/H ratio and could be acquired due to adsorption of water on fractal grains during Earth's accretion. The ocean water (and its D/H ratio) could be a result of mixing of water from several sources.

2. Migration of Jupiter-crossing objects

The orbital evolution of >30,000 bodies with initial orbits close to those of Jupiter-family comets (JFCs), Halley-type comets, long-period comets, and asteroids in the resonances 3/1 and 5/2 with Jupiter was integrated until all bodies reached 2000 AU from the Sun or collided with the Sun. Based on a set of orbital elements during evolution, we studied [4-6] the probabilities of collisions of migrating bodies and

particles (during their dynamical lifetimes) with planets. The mean value of the probability p_E of a collision of considered JFCs with the Earth exceeded 4×10^{-6} . The ratio of mass of water delivered to a planet by such bodies to its bulk mass could be greater for Mars, Venus, and Mercury, than that for Earth. This larger mass fraction would result in relatively large ancient oceans on Mars and Venus.

3. Migration of dust

Based on results of our integration of the orbital evolution of >20,000 dust particles produced by comets and asteroids, we studied [4-7] the probabilities of collisions of migrating particles (during their dynamical lifetimes) with planets. At integration we took into account the influence of planetary gravity, radiation pressure, Poynting-Robertson drag, and solar wind drag. For dust particles, p_E was found to have a maximum (~ 0.001 - 0.02) at diameters of particles $\sim 100 \mu\text{m}$. A large amount of material (including water and volatiles) could be delivered by dust particles to the zone of the terrestrial planets from the zone of Jupiter and Saturn just after gas left the latter zone, which could contain a lot of dust. In the present solar system, the amount of matter delivered by dust particles to the Earth can be smaller than that delivered by bodies only by a factor of a few. Dust particles could be more effective than bodies in delivery of organic matter because they less warm up in the atmosphere.

4. Migration of planetesimals from the feeding zone of Jupiter and Saturn

Recently we made computer simulations of migration of 10^4 planetesimals from the feeding zone of Jupiter and Saturn to forming terrestrial planets under the gravitational influence of planets. In series JN, all planets were assumed as having their present orbits and masses. In series JS, Uranus and Neptune were

excluded. Initial eccentricities and inclinations of planetesimals were 0.3 and 0.15 rad, respectively. The initial semi-major axes of the planetesimals were between 4.5 and 12 AU. Masses of planets moving in the orbits of the terrestrial planets were equal to present masses of the planets in series JS and JN. In series JS₀₁ and JN₀₁, they were smaller by a factor of 10 than the present masses. We also made calculations for which the giant planets of present masses initially were located more close to each other than the present giant planets. For such runs, at least one giant planet (not Jupiter) was ejected into a hyperbolic orbit during evolution. The values of the probability p_E of a collision of a planetesimal with the Earth for such runs were usually not smaller than the values of p_E for series JS, JN, JS₀₁ and JN₀₁.

The results of the calculations showed that the ratio of the fraction of the planetesimals collided with the Earth's embryo was about 2×10^{-6} and 4×10^{-7} for the mass of the embryo equal to the Earth mass m_E and to $0.1m_E$, respectively. We concluded that during the growth of the mass of the Earth's embryo up to $0.5m_E$, the amount of water delivered to the embryo from the feeding zone of Jupiter and Saturn could be about 30% of the total mass of water delivered to the Earth from this feeding zone. The total mass of water delivered to the Earth from the feeding zones of the giant planets and from beyond these zones could be comparable with the mass of the Earth's oceans. The total mass of the Earth's ocean water is about $2.25 \times 10^{-4} m_E$. At $p_E = 2 \times 10^{-6}$, for the total mass of planetesimals in the feeding zone of Jupiter and Saturn equal to $100m_E$, and planetesimals consisted half in water, the planetesimals from this feeding zone could deliver about a half of Earth's ocean water. Another half of the water could come from more distant regions. Most of the water that was delivered from such distant regions to the Earth's embryo came when its mass was not small (e.g., was mainly greater than $0.5m_E$). In series JS, the ratio of the mass of water delivered to a planet to the mass of the planet for the Earth was smaller by a factor of 2, 1.25, and 1.3 than that for Mars, Venus and Mercury, respectively. For series JN, the above factor equaled to 3.4, 0.7 и 0.8, respectively. For the growth of Earth's embryo of mass m by accretion of planetesimals that came from the feeding zone of Jupiter and Saturn, the increase of its mass turned out proportional to $m^{0.74}$.

In our calculations of the migration of the objects which initially moved in cometary-type Jupiter-crossing orbits, the fraction p_E of the objects collided with the Earth exceeded 4×10^{-6} [4-6]. These values of p_E were greater than the above mentioned values of p_E for planetesimals because initial eccentricities of planetesimals were smaller than those of cometary objects, and not all planetesimals reached Jupiter's orbit during their lifetimes. If one takes into account the mutual gravitational influence of planetesimals, then they would get greater eccentricities during evolution and the values of p_E would be greater than those for the model which does not consider the mutual gravitational influence of planetesimals. Orbits of Earth-crossing objects that migrated from outside Jupiter's orbit are typically highly eccentric. For such eccentric orbits, the effective radii of the Earth and the Moon are approximately proportional to their radii, and the amount of the material, including water, delivered to the Moon from outside Jupiter's orbit could be only by an order of magnitude smaller than that delivered to the Earth.

Acknowledgements

The work was supported in part by the grant of Russian Science Foundation N 17-17-01279 and by the Program of Fundamental Studies of RAS № 22.

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Formation of TRAPPIST-1

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Abstract

We present a model for the formation of the recently-discovered TRAPPIST-1 planetary system. In our scenario planets form in the interior regions, by accretion of mm to cm-size particles (pebbles) that drifted from the outer disk. This scenario has several advantages: it connects to the observation that disks are made up of pebbles, it is efficient, it explains why the TRAPPIST-1 planets are \sim Earth mass, and it provides a rationale for the system's architecture.

1. Introduction

TRAPPIST-1 is an M8 main-sequence star located at a distance of 12 pc. It has recently been observed to harbor seven planets, all within 0.1 au and all with radii inferred to be around $\sim 1 R_{\oplus}$ [1]. From transit timing analysis the planets are consistent with a rocky composition, although solutions where planets harbor significant amounts of H_2O (ice) are also possible.

Since the stellar mass is only 8% of solar, and typical disk masses are a fraction of stellar, the TRAPPIST-1 protoplanetary disk very efficiently converted solid material into planets. TRAPPIST-1 presents a puzzle for planet formation theories, because both the *in situ* model and the *migration model* do not work very well or need extreme conditions. For *in situ* formation a very massive disk is needed. Such disks would likely be unstable and the classical formation model cannot easily explain the packed configuration. The migration scenario – where planets assemble in the outer disk, then migrate in – would fare slightly better since the disk can have a more standard size. But it offers no good explanation for the fact that the TRAPPIST-1 planets are ~ 1 Earth mass, why there are seven of them, and can only produce icy planets.

2. Our model

Figure 1 sketches our model for the formation of the TRAPPIST-1 planets [7]. Pebbles form in the outer disk by coagulation of dust grains, until they

start to drift by aerodynamical drag. However, this growth+drift occurs in an inside-out fashion, which does not result in strong particle pileups needed to trigger planetesimal formation by, *e.g.*, the streaming instability [3]. (a) We propose that the H_2O iceline ($r_{ice} \approx 0.1$ au for TRAPPIST-1) is the place where the local solids-to-gas ratio can reach ~ 1 , either by condensation of the vapor [9] or by pileup of ice-free (silicate) grains [2, 8]. Under these conditions planetary embryos can form. (b) Due to type I migration, embryos cross the iceline and enter the ice-free region. (c) There, silicate pebbles are smaller because of collisional fragmentation. Nevertheless, pebble accretion remains efficient and growth is fast [6]. (d) At approximately Earth masses embryos reach their *pebble isolation mass* – the mass where a shallow gaps in the gas disk is opened that arrests further pebble accretion [4]. The planet then migrates further to the inner disk edge r_c , the stellar magnetospheric cavity radius. Meanwhile a second embryo forms at the iceline, which undergoes an evolution similar to its elder sibling. Stages (a)–(d) repeat until the pebble flux from the outer disk subsides.

(e) Convergent migration of planets in dissipative media like gas-rich disks, causes them to be trapped in resonances. We assume that planets get trapped in first order mean motion resonances, close to the period ratios in which they are presently observed. The system remains in this state until the disk starts to decay.

However, the period ratios of planets b/c and c/d are currently not close to any first-order integer commensurability. We propose that the current architecture is set during the disk clearing phase through a processes named *magnetospheric rebound* [5]. Simply put, it means that the inner disk edge (r_c) expands as the disk loses mass. In principle, disk-planet interaction causes the inner planet to be tied to the expanding r_c , but this coupling will break when the expansion of r_c is too rapid. We have tuned the parameters of the magnetospheric rebound model in order to match the architecture of TRAPPIST-1. This implies that there are two dispersion phases: (f) an initial phase where r_c stalls between planets c and d, after which the system mi-

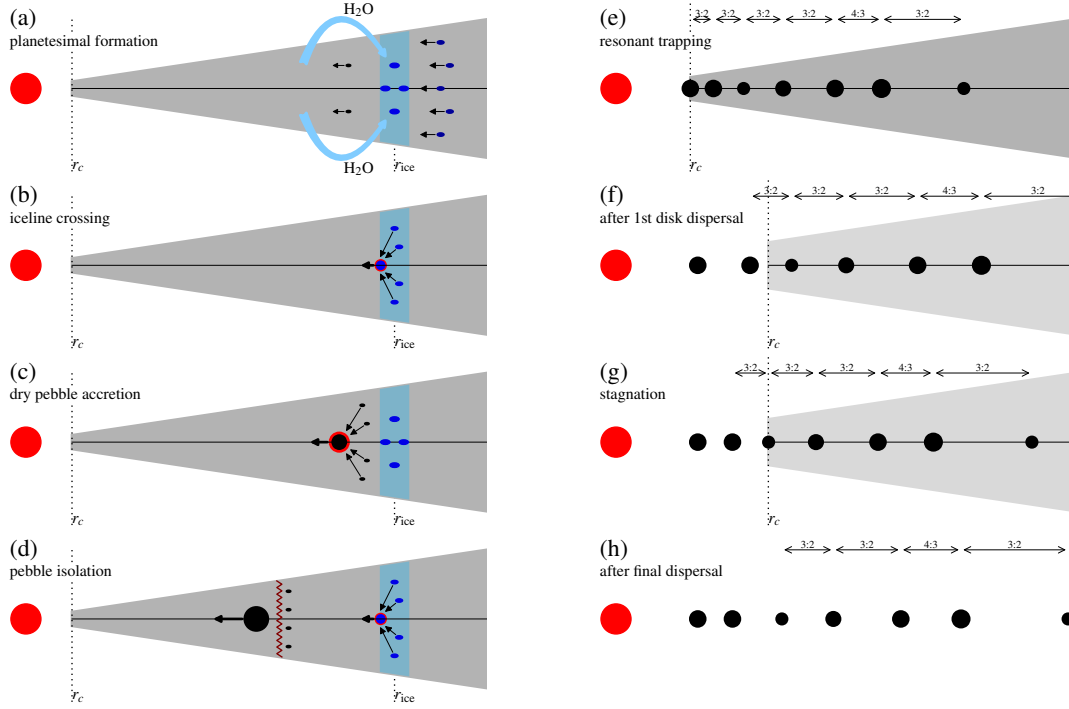


Figure 1: Sketch of the formation of TRAPPIST-1. Described in the main text.

grates in again, such that planet d now coincides with r_c (g); and a final dispersion phase, which moves c/d out of resonance, because of divergent migration, resulting in a configuration that by-and-large resembles the present one (h).

3. Implications and Outlook

In our proposed scenario it is not the planets but the planetary building blocks that migrated. Many M-stars observed with *Kepler* feature such a concentration of close-in planets, similar to TRAPPIST-1. However, such a scenario would be hard to envision when the pebble flux is blocked by, for example, a giant planet *beyond* the H₂O iceline. Hence, within the context of the proposed scenario, close-in planets would preferentially form in systems that failed to form a gas giant. On the other hand, in systems where a giant planet did form early planet formation proceeded towards outer gas and ice giants.

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How can periodic orbits puzzle out the coexistence of terrestrial planets with giant eccentric ones?

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Abstract

Hitherto unprecedented detections of exoplanets have been triggered by missions and ground based telescopes. The quest of “exo-Earths” has become intriguing and the long-term stability of planetary orbits is a crucial factor for the biosphere to evolve. Planets in mean-motion resonances (MMRs) prompt the investigation of the dynamics in the framework of the three-body problem, where the families of stable periodic orbits constitute the backbone of stability domains in phase space. In this talk, we address the question of the possible coexistence of terrestrial planets with a giant companion on circular or eccentric orbit and explore the extent of the stability regions, when both the eccentricity of the outer giant planet and the semi-major axis of the inner terrestrial one vary, i.e. we investigate both non-resonant and resonant configurations. The families of periodic orbits in the restricted three-body problem are computed for the 3/2, 2/1, 5/2, 3/1, 4/1 and 5/1 MMRs. We then construct maps of dynamical stability (DS-maps) to identify the boundaries of the stability domains where such a coexistence is allowed. Guided by the periodic orbits, we delve into regular motion in phase space and propose the essential values of the orbital elements, in order for such configurations to survive long time spans and hence, for observations to be complemented or revised.

1. Introduction

Many systems consist of more than one planet and the study of planetary orbits in relation to their long-term stability is crucial. Dynamical studies are essential to determine, whether a given planet can remain stable for long time spans [1]. The sustainability of habitable terrestrial exoplanets, under the effect of another giant planet, whether in resonance, or not, can prove to be a fruitful venture [2, 3].

Using the elliptic restricted three-body problem (ERTBP) as a model, the computation of families of

periodic orbits in a suitable rotating frame of reference acts as a diagnostic tool, which can help ascertain information regarding the phase space in planets’ vicinity.

2. Model set-up

We focus on internal MMRs and let two planets of masses m_1 and m_2 , revolve around a star of mass m_0 , with $m_0 = 1 - m_2$, $m_1 = 0$ and $m_2 = 0.001 = m_J$. We herein restrict our study to coplanar planetary orbits, which correspond to Keplerian ellipses, in the inertial frame, described by heliocentric osculating elements, namely the semimajor axes, a_i , the eccentricities, e_i and the longitudes of pericentre, ϖ_i . For the position of the planets on the osculating ellipse, we consider the mean anomalies, M_i . Subscripts 1 and 2 refer to the inner and the outer planet, respectively. We focus on symmetric periodic orbits, where the apsidal difference is $\Delta\varpi = 0$ or π .

3. DS-map set-up

DS-maps can depict each neighbourhood in the phase space of a planetary system. By creating grids of initial conditions, after having chosen the periodic orbit being closer to the dynamical vicinity of interest, we colour each condition based on the output of a chaotic indicator and in particular, the DFLI. We perform a thorough study by considering eccentricity values $e_1 = 0.02, 0.1, 0.3$ and 0.5 while $e_2 \in [0, 1]$. Therefore, we showcase the domains where such planetary systems could be hosted.

4. Results

We show the families of periodic orbits that belong to the 3/2, 2/1, 5/2, 3/1, 4/1 and 5/1 MMRs in the ERTBP and then, connect the islands of stability that appear on the DS-maps with the stable periodic orbits. Finally, we present a precise exploration of the phase space

with regards to the extent of those domains when the eccentricities and the angles vary.

In Fig. 1, we depict a particular result taken from one family (blue curve) at 2/1 MMR. It is straightforward that the stable periodic orbits constitute the core of domains where the motion is regular (dark region) and the long-term stability is guaranteed. Within this representative case, we can argue that an inner terrestrial planet can survive long time spans in MMR with a giant highly eccentric outer planet on coplanar symmetric orbits, even when both orbits are highly eccentric.

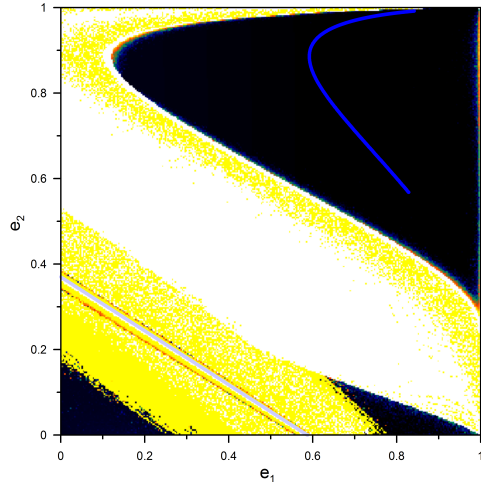


Figure 1: A DS-map on the eccentricities' plane, which showcases stable (dark) and chaotic (pale) domains in the phase space of a stable 2/1 resonant symmetric periodic orbit belonging to the family (bold blue curve) with $\varpi_1 = M_1 = \pi$ and $\varpi_2 = M_2 = 0$.

5. Summary and conclusions

We study the dynamics of planetary systems consisting of a giant and a terrestrial planet in all major MMRs in the ERTBP and present the phase space in their vicinity. Being motivated by the quest of Earth-like habitable planets we provide all possible stability domains for coplanar symmetric orbits, which are built about stable periodic orbits.

In that respect, this study is essential for the research of terrestrial planets among the systems with giant planets, which have already been discovered and will assist in refining particular observational data.

Acknowledgements

This work was supported by the Fonds de la Recherche Scientifique-FNRS under Grant No. T.0029.13 (“ExtraOrDynHa” research project). Computational resources have been provided by the Consortium des Équipements de Calcul Intensif (CÉCI), funded by the Fonds de la Recherche Scientifique de Belgique (F.R.S.-FNRS) under Grant No. 2.5020.11.

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Formation and growth of embryos of the Earth and the Moon

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Abstract

The model of the formation of the embryos of the Earth and the Moon as a result of contraction of the same parental rarefied condensation is discussed. The angular momentum of the condensation needed for such formation could be mainly acquired at the collision of two rarefied condensations at which the parental condensation formed.

Introduction

Many authors suppose that the Earth-Moon system formed as a result of a collision of the solid Earth with a Mars-size object. Galimov and Krivtsov [1] presented arguments that the giant impact concept has several weaknesses. Lyra et al. [2] showed that in the vortices launched by the Rossby wave instability in the borders of the dead zone, the solids quickly achieve critical densities and undergo gravitational collapse into protoplanetary embryos in the mass range $0.1M_E$ - $0.6M_E$ (where M_E is the mass of the Earth). Ipatov [3-5] and Nesvornyy et al. [6] supposed that trans-Neptunian satellite systems formed by contraction of rarefied condensations.

1. Formation of the embryos of the Earth and the Moon at the stage of condensations

Galimov and Krivtsov [1] made computer simulations of the formation of the embryos of the Earth and the Moon as a result of contraction of a rarefied condensation. The angular momentum K_s needed for such contraction could not be acquired during formation of the condensation from a protoplanetary disk. Using the formulas presented in [2], we obtained that the angular momentum K_{SEM} of the present Earth-Moon system could be acquired at a collision of two rarefied condensations with a total

mass not smaller than $0.1M_E$. In principle, the angular momentum of the condensation needed for formation of the Earth-Moon system could be acquired by accumulation only of small objects. In this case, there could be $K_s=K_{SEM}$ for a parental condensation with mass $m>0.2M_E$. However, if K_s of parental condensations for all embryos of terrestrial planets grew only during accumulation of small objects by the condensations, then all these planets would have large satellites. Probably, the condensations that contracted and formed the embryos of the terrestrial planets other than the Earth did not collide with massive condensations, and therefore they did not get a large enough angular momentum needed for formation of massive satellites. The embryos formed as a result of contraction of the condensation grew by accumulation of solid planetesimals. The mass of the rarefied condensation that was a parent for the embryos of the Earth and the Moon could be relatively small ($0.02M_E$ or even less), if we take into account the growth of the angular momentum of the embryos at the time when they accumulated planetesimals.

In our estimates of K_s discussed above, the radius of the parental condensation with the angular momentum needed for the formation of the embryos of the Earth-Moon system was comparable with the Hill radius r_H and was greater than the radius of a parental gas-dust condensation equal to $0.023r_H$ considered in [1]. At such small radius of the dust condensation, Galimov and Krivtsov [1] obtained evaporation of iron and the formation of almost iron-free embryos of the Earth and the Moon. In order to get the angular momentum needed for formation of a satellite system, the condensation considered by Galimov and Krivtsov had to be a result of a compression of the condensation with a larger size than that considered in [1]. After the compression of the condensation to radius of $0.023r_H$, it could contain objects greater than dust. Some scientists (e.g., [7]) consider that condensations in the

terrestrial feeding zone could consist of objects of decimeter size, which were greater than dust.

2. Growth of solid embryos of the Earth and the Moon

For the case of small relative velocities of planetesimals, effective radii r_{ef} of the embryos are proportional to r^2 , where r is the radius of a considered embryo. In this case, $m_{Mo}^{-1/3} = m_M^{-1/3} + k_2 m_{E0}^{-1/3} - k_2 m_E^{-1/3}$, where $k_2 = k_d^{4/3}$, k_d is the ratio of the density of the growing Earth of mass m_E to that of the growing Moon of mass m_M ($k_d \approx 1.65$ for the present Earth and Moon), m_{Mo} and m_{E0} are initial values of m_M and m_E . For $m_M = 0.0123 m_E$, $m_{E0} = 0.1 m_E$, $m_E = M_E$ the above equation is true at $k_2 = 1$ and $m_{Mo} = 0.00605 M_E$, and also at $k_2 = 1.65$ and $m_{Mo} = 0.0035 M_E$. For such data, the mass of the Moon grew by a factor of 2 – 3.5 while the Earth embryo grew by a factor of 10. At r_{ef} proportional to r^2 , the embryo of the Earth grew faster than that of the Moon. For large enough eccentricities of planetesimals, the effective radii of proto-Earth and proto-Moon were proportional to r . In this case $m_{Mo}^{1/3} = m_M^{1/3} + k_1 m_{E0}^{1/3} - k_1 m_E^{1/3}$ (where $k_1 = k_d^{2/3}$) and the increase of m_M/m_{Mo} is greater than that of m_E/m_{E0} .

According to Galimov and Krivtsov [1], initial embryos of the Earth and the Moon were almost free from iron, and the Earth got more iron than the Moon because it grew faster by accumulation of dust. Let us consider the following simple model: The initial embryos didn't contain iron, and the incoming material contains 33% of iron. For a considerable growth of the mass of Earth embryo, the final fraction of iron in the embryo can be close to the present 32%. The fraction of iron in the Moon would be $0.33(1 - m_{rMo})$, где m_{rMo} is the ratio of the initial mass of the Moon embryo to the present mass of the Moon. Taking the present fraction of iron in the Moon to be equal to 8% and solving $0.33(1 - m_{rMo}) = 0.08$, we get $m_{rMo} = 0.76$ and the growth of the Moon embryo by a factor of 1.3. This estimate is in accordance with the estimates by Galimov and Krivtsov [1] of the growth of the Moon embryo by a factor of 1.31 at the growth of the mass of the Earth embryo by a factor of 26.2. For the above formula, the fraction of iron in the Earth is $0.33(1 - 1/26.2) = 0.317$. At r_{ef} proportional to r^2 or to r , the growth of the Moon embryo is faster than it is needed to obtain the present fraction of iron in the Moon for growth of the Earth embryo mass by a factor of 26. May be at the gas/dust stage the relative growth of

the Earth embryo was faster than at r_{ef} proportional to r^2 . For growth of the Earth embryo by accretion of solid planetesimals, its initial mass could not differ by an order of magnitude or more from the present mass of the Earth if we try to explain the differences in the fractions of iron in the Earth and the Moon.

Note that one more collision (or a series of collisions) of a parental condensation or a solid Earth embryo with a massive object is needed to change the tilt of the Earth to its present value. It could be at the stage of solid embryos or at the stage of condensations if at a collision the radius of the Earth embryo condensation was smaller than the semi-major axis of the orbit of the Moon embryo condensation around the Earth embryo condensation.

I suppose that the problem of formation of iron-free embryos as a result of compression of a condensation need to be more clarified, e.g. for the case when the parental condensation consisted of larger objects than dust. May be the objects had fractal structure and their evaporation was close to that considered in [1]? The model of the formation of a solid planet with a large enough satellite can work for some exoplanet.

Acknowledgements

The work was supported by the grant of Russian Science Foundation N 17-17-01279.

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The formation of mini-Neptunes

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Abstract

The results of the Kepler mission show that planets smaller than Neptune ("mini-Neptunes"), presumably composed of non-negligible amounts of hydrogen and helium, are frequent. The formation of this type of objects is in principle challenging for the classical core-accretion paradigm of giant planet formation. We show that mini-Neptunes are a common outcome when including the effect of envelope enrichment by icy planetesimals/pebbles in the formation models. We will discuss as well the planetary composition/structure, and the implications for the interpretation of exoplanet observations.

Water transport and water loss by collisions during planet formation

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Abstract

In this contribution, we present results of collision simulations pertaining to water loss covering body masses ranging from a small planetary embryo to the mass of Earth. We find that for most realistic combinations of object masses, collision velocities, and impact angles a considerable amount of water is lost, which may significantly change the water inventory of formed terrestrial planets. Also, there is indication that beyond the ‘usual’ parameters characterizing a collision (velocity expressed in units of the mutual escape velocity v_{esc} and impact angle), water loss depends on factors like absolute mass, the projectile-target mass ratio, and to a certain extent the water distribution inside the objects.

1. Introduction

It is well established that planet formation involved a long-term sequence of collisional events between protoplanetary bodies. Typically, dynamical evolution studies use n-body simulations to investigate this collisional growth, but simplify the collision model based on perfect inelastic merging and linear momentum conservation (e.g., [9, 11]) or the application of simple fragmentation models ([2]). However, depending on the involved masses, collision speeds, and the impact angle (e.g., [10]) the collision outcome is one of efficient accretion/perfect merging, partial accretion, hit-and-run, or erosion and disruption ([3]). The perfect merging assumption does not model the actual physics of collisions ([1, 3]).

While water transport in giant impacts has been investigated (e.g., [7, 15]), the fate of volatiles such as water in small to mid scale collisions – which dominate at least the early stages of planet formation – remains largely unstudied. Existing planet formation simulations overestimate the water content of terrestrial planets. [8] study planet formation in binary sys-

tems and estimate an artificial increase of their water contents by a factor of 5–10; [16] use the perfect merging assumption for planet formation in single star systems and estimate their water contents to be accurate only within a factor of two.

2. Method

We perform simulations with our parallel 3D smooth particle hydrodynamics (SPH) code as introduced in [13] and [17]. It implements solid state continuum mechanics extended by a model for simulating brittle failure (cf. [5, 6]) and includes self-gravity. We apply a tensorial correction along the lines of [18] to achieve first-order consistency.

The material model is based on the Tillotson equation of state ([19]). We use the same material parameters for rock (basalt) and water ice as stated in [17].

In the individual scenarios described below we resolve the objects into between 20k SPH particles for the parameter study of Ceres-sized colliding bodies and one million SPH particles for the collision of a small planetary embryo with an object of Earth mass.

3. Results and conclusion

We performed three suites of simulations in different mass regimes, totaling to some 60 scenarios: (a) Ceres mass objects with velocities and impact angles from a dynamical study in a solar system-like environment ([12]); (b) larger planetary embryo collisions from n-body simulations by [9]; (c) Ceres-sized projectiles hitting planet-size targets in binary star systems at higher speed from [4].

Figure 1 summarizes the water loss resulting from the three suites of scenarios for one particular impact angle $\alpha = 30^\circ$ (measured from the vertical, chosen because it occurs in all three scenario sets) and several collision velocities up to $6 v_{\text{esc}}$. We define water loss as the ratio of the water-mass not gravitationally

bound to the surviving object(s) and the total initial water. Please refer to [14] for a more comprehensive discussion of the simulation results.

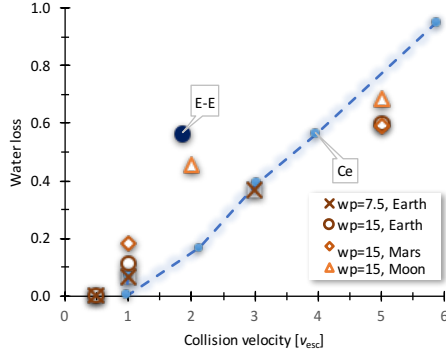


Figure 1: Water loss (y-axis) at a given impact angle (here, 30°). It not only depends on the collision velocity (x-axis), but also on absolute body mass (light blue: Ceres mass, dark blue labeled ‘E-E’: embryos of $0.5 M_{\text{Mars}}$ and $0.8 M_{\text{Moon}}$, brown: Ceres mass projectiles with different water content wp hit planet-sized targets as indicated).

Our results show that even for collisions at moderate speed water loss is not negligible – for embryos colliding at twice their mutual escape velocity as much as 10 % . . . 60 % of their water content are lost *per collision*. Keeping in mind that (a) evaporation and sublimation further increase water loss and (b) a long series of collisions may happen until a planet is formed, it gets obvious that the assumption of perfect merging – in particular 100 % accretion of volatiles – whenever a collision occurs does not hold. Present n-body based planet formation simulations suggest terrestrial planet water abundances which are too high by up to a factor of 5–10 (cf. [8, 16]). Finding a way to combine realistic collision simulations and n-body studies will likely close this gap between reality and simulations.

Acknowledgements

TIM, CB, and RD acknowledge support from the FWF Austrian Science Fund under project S11603-N16. NH acknowledges support from NASA PAST program under grant NNX14AJ38G. DB acknowledges support from the FWF Austrian Science Fund under project S11608-N16.

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A possible scenario of the formation of our solar system in a gas depleted disk

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Abstract

First, we study the final masses of giant planets growing in protoplanetary disks through capture of disk gas, by employing empirical formulae for the gas capture rate and a shallow disk gap model, which are both based on hydrodynamic simulations. We find that, for planets less massive than 10 Jupiter masses, their growth rates are mainly controlled by the gas supply through the global disk accretion, and the gap opening does not limit the accretion. The insufficient gas supply compared with the rapid gas capture causes a depletion of the gas surface density even at the outside the gap, which can create an inner hole in the disk. Second, our findings are applied to the formation of our solar system. For the formation of Jupiter, a very low-mass gas disk of several Jupiter masses is required at the beginning of its gas capture because of the continual capture. Such a low-mass gas disk with sufficient solid material can be formed through viscous evolution from a compact disk of initial size ~ 10 au. By viscous evolution with a moderate viscosity of $\alpha \sim 10^{-3}$, most of the disk gas accretes onto the Sun and a widely spread low-mass gas disk remains when the solid core of Jupiter starts gas capture at $\sim 10^{-7}$ yr. A very low-mass gas disk also provides a plausible path where type I and II planetary migrations are both suppressed significantly. In particular, the type II migration of Jupiter-size planets becomes inefficient because of the additional gas depletion due to the rapid gas capture by such planets.

1. Introduction

Giant planets like Jupiter and Saturn are thought to be formed in a gas disk by capturing the disk gas [4][5]. The gas-accretion growth of a giant planet is expected to be terminated when the planet's own strong gravity creates a gap. Two well-known gap-opening conditions have been widely used: the thermal condition and the viscous condition [2]. After a while, an analytic formula for the gap profile was suggested [6], which gives shallower gap than

the traditional conditions. However, recent hydrodynamic simulations have shown that the gap is much shallower than the traditional prediction, and even shallower than the analytic estimate. This means that the formation of gap would be more difficult than previously thought, and thus this forces us to reconsider the mechanism to terminate the growth of the giant planets.

In this study, we construct a toy model to describe the giant planet growth by capturing protoplanetary gas disks, and examine the final masses of the giant planets. We then apply the model to our solar system, and suggest a possible scenario of the formation of our solar system by considering the shallower gap model.

2. Methods

We consider a globally evolving protoplanetary disk with the self-similar solution. In the disk, a proto-giant planet starts to capture the disk gas with a rate given by our model. The formula of the gas accretion rate onto the planet is given by the combination of the three terms:

$$\dot{M}_p = \min(\dot{M}_{p,hydro}, \max(\dot{M}_{d,global}, \dot{M}_{d,local})),$$

where $\dot{M}_{p,hydro}$ is the gas accretion rate onto the planet by hydrodynamic gas flow, $\dot{M}_{d,global}$ is the steady-state radial accretion rate in the global viscous disk, and $\dot{M}_{d,local}$ is the transient viscous disk accretion rate just after the planet starts the gas capturing growth. The term $\dot{M}_{p,hydro}$ considers the hydrodynamic gas accretion onto the planet [7], and the gap deepening [1], both of which are based on the numerical simulations. The three terms are given in explicit functions of disk mass, disk scaleheight, viscous coefficient, disk initial size, planet mass and orbital radius, and time after the onset of the gas capture. Once we obtain the formula of the accretion rate explicitly, we can integrate the formula with respect to time, which gives us the evolution and history of the giant planet growth.

3. Results

We performed a parameter study systematically, and found that, for planets less than 10 Jupiter masses, their growth rates are mainly controlled by the gas supply through the global disk accretion. This means that the gap is no effect to reduce the gas accretion rate onto the planets until they reach 10 Jupiter masses.

4. Possible scenario of the formation of our solar system

If the gap is little effect to reduce or terminate the growth rate, the final mass would be much larger than the current Jupiter mass if we consider the “standard” disk model. Thus a very low-mass gas disk is required when the proto-giant planet starts the dynamical gas capture. But at the same time, enough solid mass is required to produce the solid cores that can trigger the dynamical gas accretion. To solve the difficulty, we here propose that the initial protoplanetary disk is a very compact (~ 10 AU) with about 18 Jupiter masses with the solar composition. In the dense disk, dust growth is very fast to be planetesimals, and quickly decoupled from the disk gas. The following disk viscous accretion onto the star reduces disk gas only, not for the planetesimals, which realize the low-mass gas disk with high metallicity. When the gas disk is reduced to be around 4 Jupiter masses, the solid core reaches the critical mass (~ 10 Earth masses) and starts the gas capture. This scenario is also preferable in terms of type I and II migrations. If solid protoplanets grows in the gas-depleted disk, type I migration rate is reduced and the longstanding problem of falling solid planets is mitigated to considerable degree. In addition, our model consider the local depletion of disk gas near the planet orbit in steady state [3], which even reduces torque from the disk onto the planet. Figure 1 shows the growth-migration curves of the protoplanets in the gas capturing phase. Our model reproduces the population of the extrasolar system, which is very difficult by the previous prediction.

Acknowledgements

This work was supported by JSPS KAKENHI grant numbers 26800229, 15H02065, 26287101.

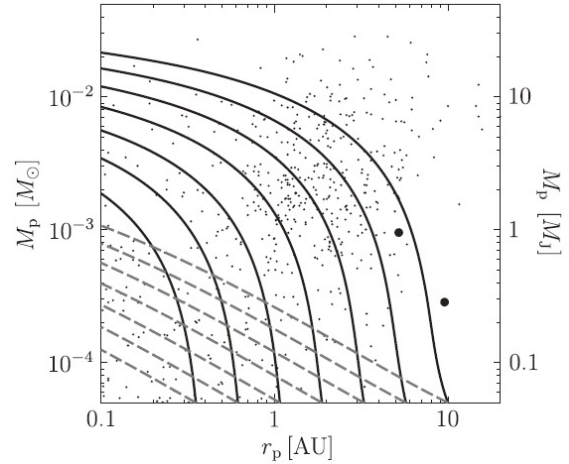


Figure 1. Growth-migration curves. Solid curves show evolution paths based on our result, and dashed curves are the cases where the traditional type II migration is used. Small dots show the distribution of extrasolar planets. Filled circles are Jupiter and Saturn.

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Water transfer and loss in hit-and-run collisions

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Abstract

This work focuses on transfer and loss of volatiles, like water, in hit-and-run collisions, where especially the smaller one of the colliding pair is often stripped of considerable amounts of its initial volatile content, but still survives the encounter more or less intact. We find water losses up to 75% in a single collision, depending on various parameters, especially velocity, impact angle and mass ratio, but also on the total colliding mass. The physical state, especially vaporization of volatiles, is found to be particularly important in collisions of \sim Mars-sized bodies, with high impact energies, but still potentially easy volatile escape.

1. Introduction

The formation of (terrestrial) planets is believed to end with a phase dominated by similar-sized collisions between planetary embryos, once the gas disk disappears and dynamical friction by planetesimals becomes inefficient. It is characterized by chaotic interactions and mixing of material originating from different locations in the disk (e.g., [7]) which shape the final characteristics and composition of planets. Volatile material like water(-ice) is particularly affected by transfer and loss processes, also because they are preferentially found in the outer layers of (partly) differentiated bodies. Studies of late-stage accretion by means of N-body simulations mostly treat collision outcomes only rudimentary, if at all, where perfect merging is still an often-used assumption. This falsifies results in general, and even more for volatile inventories (see e.g., [5, 2]). While impacts of small bodies on much larger ones are usually hit-or-miss events, a broad range of distinct outcomes is possible for collisions between similar-sized bodies ([6]). For head-on collisions they transition from accretion to erosion with increasing impact velocity, but for sufficiently oblique collisions an additional outcome regime emerges: hit-and-run. These encounters are characterized by 2 large surviving bodies, or even by a large one and a chain of

smaller ones. Having more than one large survivor makes them difficult to track, but also interesting, and important to the fate of volatiles (and also to various other questions, like Mercury's large core). Recent results have shown that up to half of all giant collisions in an active planet formation environment are actually from the hit-and-run type (e.g., [4]), therefore understanding their characteristics is a necessity for a realistic treatment of volatile transport in the next generation of N-body simulations.

2. Method and scenarios

We perform collision simulations of self-gravitating, differentiated (iron core – basaltic mantle – water ice shell), embryo-sized bodies with our SPH code ([8]), which allows us to study the dynamical fate and also the physical state of volatile inventories during and after a hit-and-run collision. The parameter space is large, where the impact velocity v/v_{esc} , impact angle α , mass ratio γ and also overall mass M_{tot} ([3]) are the most important ones. We ran a suite of simulations with typical impact velocities up to several times v_{esc} , impact angles between 30° and 90° , mass ratios ranging from 1:2 up to 1:50, and total masses between 10^{22} and 10^{25} kg. The majority of simulations comprise hydrodynamical objects, but we also compare them to results obtained with our solid-body material model to clarify the influence of material strength.

3. Results and conclusions

In general the impact energy is partitioned between the projectile and the target, thus the projectile is proportionally more affected the lower the mass ratio. Disrupting bodies via impacts (by smaller projectiles) has been found to be very difficult once they grow large enough (e.g., [1]), which we can confirm also for their volatile contents, albeit to a lesser degree. Focusing on the smaller of the two survivors in a hit-and-run collision provides a new perspective to that, since they outline a reasonable path towards stripping large bodies

of volatiles or even disrupting them entirely, once they are hit by an even larger body. Our results confirm that neither of the two largest fragments ever increases its water mass fraction. The largest fragment (initially the target) barely loses mass and only little volatiles (cf. Fig. 1), except for low impact angles and high velocities, but the projectile is much more affected, with water losses up to 75% in a single collision. Since objects are expected to suffer a sequence of giant collisions in the late stages of planet formation this clearly indicates that the usual assumption of perfect merging is highly inaccurate, particularly w.r.t. volatile components.

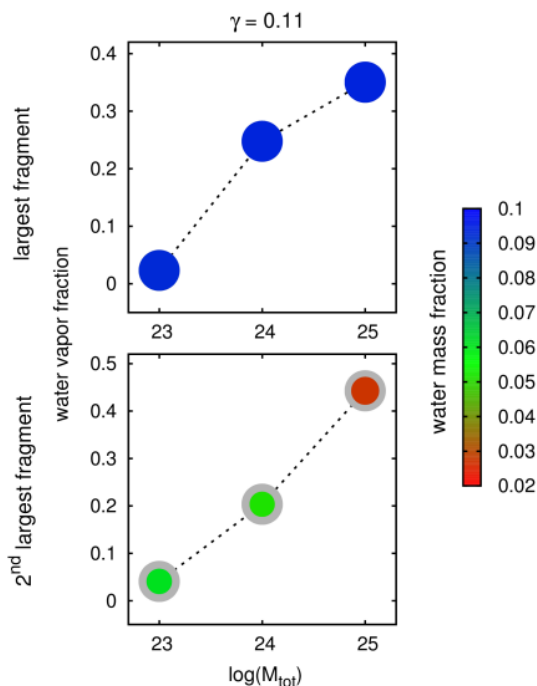


Figure 1: Water vapor fraction on the 2 largest post-collision fragments as a function of total colliding mass (kg), with all other parameters equal ($v/v_{\text{esc}} = 2.5$, $\alpha = 45^\circ$, $\gamma = 1:9$). The grey circles indicate pre-collision sizes of the projectile and the color-coding illustrates the water mass fraction (all states) after the collision, which is initially 0.1 for both bodies.

In order to better understand the mechanisms leading to stripping of volatile layers it is instructive to clarify which physical processes dominate under which collision conditions. This includes purely mechanical effects (like shears) as well as shock acceleration. We also track the physical state of water reservoirs, especially the amount of vaporized material (mainly due to shocks), where we estimate the ra-

tio of vaporized to non-vaporized water after the collision for a broad range of masses – and thus collision energies. Figure 1 illustrates this for a subset of our scenarios. Overall we find water vapor fractions on the two large surviving fragments essentially spanning the whole possible range between 0 and 1. Especially our intermediate mass scenarios (\sim Mars-sized bodies) are interesting in this respect, because impact energies are already high enough for large scale vaporization, but the collision fragments are still small enough for potential escape of considerable amounts of water vapor.

For a relatively narrow range of parameters the target survives quite intact, but the projectile is ripped into a chain of small, but still planetesimal-sized (around 0.1% of M_{tot}) fragments, mostly sharing the chemistry of their precursor body. We find that these chain elements tend to be increasingly dry, the more massive the colliding bodies or the more energetic the collision is, respectively. This trend is even enhanced when escape of vaporized material from these low-gravity bodies is included. Besides this compositional footprint this also implies that their significance for further water transport strongly decreases with M_{tot} .

Acknowledgements

C.B. and T.I.M. acknowledge support by the FWF Austrian Science Fund project S11603-N16.

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Migration of accreting giant planets

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Abstract

Giant planets forming in protoplanetary disks migrate relative to their host star. By repelling the gas in their vicinity, they form gaps in the disk’s structure. If they are effectively locked in their gap, it follows that their migration rate is governed by the accretion of the disk itself onto the star, in a so-called type II fashion. Recent results [3] showed however that a locking mechanism was still lacking, and was required to understand how giant planets may survive their disk. We propose that planetary accretion may play this part, and help reach this slow migration regime.

1. Introduction

Planets form in protoplanetary disks and interact gravitationally with them. In general, asymmetric distributions of material yield gravitational torques acting upon a planet and hence, promote angular momentum exchanges between the planet and the gas.

While several regimes have been identified (see [1] for a review), depending on the masses of both objects relative to their star, the general outcome of those interactions is a fast migration of planets towards their star as they lose angular momentum to the disk.

In this work, we focus on the type II migration, which concerns giant planets in a gap. In this regime, theoretically, the planets do not drift *with respect to* the gas, but rather *follow* the gas, as it spreads and accretes onto the star. However, it was shown [3] that giant planets migrate generally faster as they are not locked in their gap because they are able to transfer material from the inner disk to the outer disk. Here we investigate the influence of planetary accretion on this matter.

2. Type II with accretion

We ran simulations using FARGO 2D code [5]. A Jupiter mass $m_J = \frac{m_\odot}{1000}$ planet was used in a disk that

extends radially from 0.2 to 3 a_J , where a_J is Jupiter’s semi-major axis, and we assume a solar mass star $m_S = m_\odot$ to calibrate the star accretion rate. We consider an α -viscosity [6] driven accretion $\dot{M} = 3\pi\nu\Sigma$.

Planetary accretion is handled using an enhanced version of the recipe developed by [4] that was presented in [2]. During each time-step δt , a fraction $f \times \delta t$ of the material inside the Hill radius of the planet $R_H = a_P(m_P/3m_S)^{1/3}$, and m_S the mass of the host star, is removed from the simulation. We used a smooth transition function

$$\begin{aligned} \text{if} \quad & d/R_H < 0.3, \quad f(d) = 1 \\ \text{elif} \quad & d/R_H < 0.8, \quad f(d) = \cos^2(\pi \frac{d}{R_H} - 0.3) \\ \text{else} \quad & f(d) = 0 \end{aligned} \quad (1)$$

where d is the distance to the planet. We performed four simulations with different accretion rates, controlled by the parameter K as described later. Time evolution of the semi-major axis a is shown in Fig. 1.

2.1. Obtention of initial conditions

The initial density profile $\Sigma(r)$ was set to a power law that ensures an accretion rate $\dot{M} = 5 \times 10^{-8} m_\odot \text{yr}^{-1}$, with $\alpha = 3 \times 10^{-3}$. In order to keep control on the theoretical migration rate, we impose the inflow to stay constant at the outer boundary of the grid. It follows that, a stationary state is characterized by uniformity of $\dot{M}(r)$, which is what we aim for before releasing the planet.

To obtain our initial conditions for comparative migration, we prepared the simulations in two stages during which the planet’s orbital parameters were not allowed to evolve. First we slowly introduced the planet’s mass over 1000 jovian orbital periods T_J , with a smooth function of time $m_P(t) = m_J \sin^2(2\pi t/1000)$. In order to evacuate faster the gas originated in the orbital vicinity of the planet, we use planetary accretion while the mass is being introduced. Finally, we ran 150 additional orbits using each

simulation's respective value for K .

2.2. Results

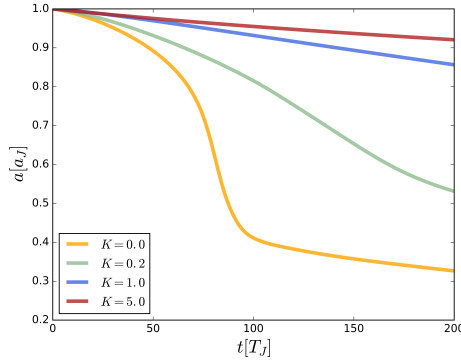


Figure 1: Semi-major axis a with respect to time t . The accretion rate $\tau_{acc}(d)$ is $Kf(d)$, where f is described by Eq. 1. Accretion slows down migration as it prevents gas to be transferred from the inner to the outer part of the disk. In this example, the accreted mass is not added to that of the planet.

When the planet migrates without accreting (orange curve on Fig. 1), it undergoes an episode of runaway migration and loses 60% of its semi-major axis in ~ 100 orbits. Any one of the accretion rates we tested here allows us to avoid this behavior. Moreover, it is evident that the migration rate \dot{a} dramatically decreases with the accretion rate. Our inter-

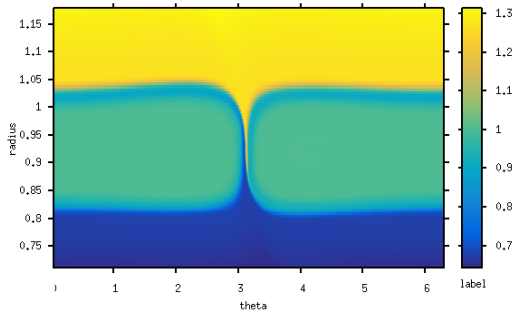


Figure 2: Colormap of the disk material's initial radius, taken $200T_J$ after releasing the planet. The planet is at $(r, \theta) = (0.93, \pi)$, accreting with $K = 5$.

pretation is that accreted material from the inner disk contributes about twice as less to the angular momentum transferred to the planet as it only survives half of the collisional encounter. Additionally, as this material can not pile up “behind” the planet, the latter can

not be pushed faster than the outer disk accretes. As shown on Fig. 2, material from the inner disk can get temporarily trapped in the so-called horseshoe region around the planet's orbit but is not transferred to the outer disk, while the latter is essentially blocked by the planet. If we add the accreted mass to the planet, the migration gets even slower still because the planet gains inertia as it migrates, while the torque provided by the disk does not scale with M_P . This allows to reduce the minimal value of the accretion rate required to restore type II.

3. Summary and Conclusions

We demonstrate that the accretion rate onto a giant planet has a dramatic influence on its migration rate. In particular, we have shown that planetary accretion prevents gas exchanges across the gap between the inner and the outer disk. This locks the planet inside its gap and restores the standard picture of type II migration. Additionally, if material from the outer disk disappears into the planet, the outer disk becomes less efficient at pushing the planet, whose migration can then be slower than type II.

Acknowledgements

We acknowledge support by the French ANR, project number ANR-13-BS05-0003-01 projet MOJO. (Modeling the Origin of JOvian planets)

The numerical computations were performed on the “Mesocentre SIGAMM” machine, hosted by the Observatoire de la Côte d’Azur.

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Impact splash chondrule formation revisited

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1. Abstract

Despite continuous efforts, a conclusive and astrophysically consistent chondrule formation scenario remains elusive. Major constraints include chemical, isotopic and textural features of chondrules, in particular retained metal abundances, bulk Fe/Mg ratios, porphyritic textures and the intra-chondrite chemical diversity. Here, we propose a coupled evolution-collision scenario in which chondrules originate from the collision aftermath of low-mass planetesimals, which are only partially molten from ^{26}Al decay. The model is consistent with the vast majority of thermal and chemical constraints and invokes a diversity of pre-chondrule material compositions. The thermo-mechanical evolution-collision regime favored in our scenario constrains the timing and formation conditions of the earliest planetesimal families and thus the onset of terrestrial planet formation.

2. Where are all the debris droplets?

Collisions among planetesimals were frequent in the early solar system [1,2,3]. These bodies were sufficiently heated by the radioactive decay of ^{26}Al to undergo intense silicate melting phases and generated large amounts of melted debris as a result from two-body interactions. In low-gravity environments, such collisional debris takes the form of myriads of small magma droplets as a result of energy conversion from lithostatic load (before the impact) to droplet surface energy (after the impact) [2].

Because chondritic meteorites are the last surviving remnants of the early accretionary phase during the lifetime of the protoplanetary disk, we should be able to identify signatures of such processes in these rocks. Therefore, if chondrules would *not* represent the aforementioned magma droplets, the meteorite collection would need to be interpreted in the sense of a virtually collision-free accretionary phase, which seems unlikely [1,2,3].

3. Magma ocean planetesimals did not generate chondrules

The most serious arguments against chondrule formation from planetesimal collisions concern the occurrence of Fe-Ni metal within chondrules or in their vicinity and the chemical and isotopic diversity of individual chondrules within the same chondrite meteorite [4]. For the first 1–2 Myr after the formation of Ca-Al-rich inclusions, the collision precursor bodies are expected to have been largely molten by ^{26}Al (internal ‘magma oceans’) [5].

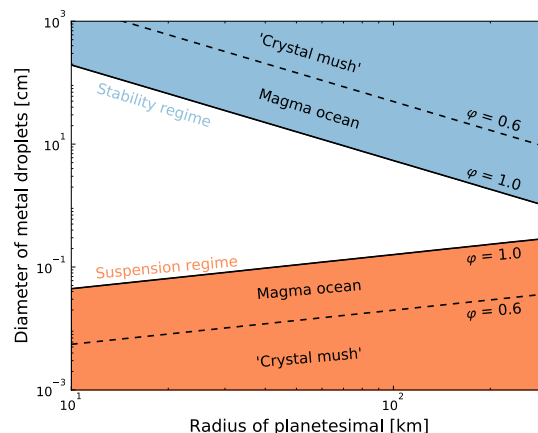


Figure 1: Metal droplets cannot be suspended in planetesimals with vigorously convecting magma oceans. The likely metal droplet sizes for various planetesimal radii and silicate melt fractions ϕ (‘stability’) in a magma ocean is shown versus the droplet sizes, which can be suspended in liquid magma by convection (‘suspension’).

Asphaug et al. [2] and Sanders & Scott [6] suggested in their models that chondrules may originate from low-velocity impacts among such magma ocean planetesimals. From a dynamical point-of-view, the apparent advantage of this scenario is that the planetesimals are already pre-molten, and impact velocities on the order of the planetesimal escape

velocity (\sim m/s) are sufficient to generate magma droplets. Such low-velocity interactions in the early solar system are expected, because the high ambient gas densities may have damped mutual collision velocities [1,2]. Testing this scenario against constraints obtained from laboratory measurements, however, we show in *Figure 1* that frequent abundances of Fe-Ni metal within and around chondrules and their chemical heterogeneity rule out excessively molten (and thus differentiated) planetesimals as chondrule precursors.

4. Chondrule properties constrain planetesimal formation and dynamical timescales

However, because the case for frequent collisional interactions in the early solar system is strong [1,2], we argue that the apparent mismatch between the chemical signatures of chondrules and the expected outcome from magma ocean planetesimal collisions allows us to reverse engineer the eligible parameter space for planetesimal formation and collision timescales, which are compliant with chondrule measurements. In contrast to the previously suggested scenario, planetesimals of preferentially low mass and/or sub-canonical ^{26}Al abundances, were significantly pre-heated but did *not* differentiate extensively (*Figure 2*).

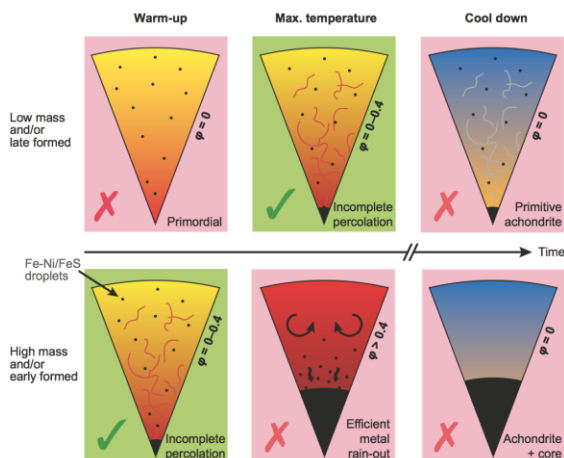


Figure 2: Suggested ‘Goldilocks’ regime for chondrule precursor planetesimals (green). Red scenarios are either chemically, texturally or isotopically inconsistent with laboratory measurements [4,7] or dynamical models [1,2,4].

By constructing dynamical scenarios for varying planetesimal families in the time from 0–5 Myr after CAIs, we argue that subsonic (\sim 1 km/s) impacts of such small-size/intermediate- ^{26}Al bodies are chemically, isotopically and texturally consistent with observations, and fit well to recent dynamical models of planet formation [1,3]. Furthermore, if different parent bodies accreted from isolated feeding zones without mutual mixing, potentially similar to the observed rings in extrasolar protoplanetary disks [8], chondrule-matrix complementarity [4] and distinct nucleosynthetic anomalies in individual chondrules may be retained.

5. Summary

Previously suggested models of impact splash chondrule formation offer attractive solutions to intertwine our understanding of planet formation with the ubiquity of chondritic meteorites. However, they suffer from major inconsistencies with the chemical and isotopic composition of chondrules. To resolve this mismatch we suggest that the vast majority of collisional debris feeding the asteroid main belt must have been derived from planetesimals, which were only partially molten. Therefore, the precursors of meteorite parent bodies either formed primarily small, from sub-canonical ^{26}Al reservoirs, or collisional growth mechanisms were efficient enough to shatter planetesimals before they reached the magma ocean phase.

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Searching for co-orbital planets by combining transit and radial-velocity measurements

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Abstract

Co-orbital planetary systems consist of two planets orbiting with the same period a central star. If co-orbital bodies are common in the solar system and are also a natural output of planetary formation models [1][2], so far none have been found in extrasolar systems. This lack may be due to observational biases, since the main detection methods are unable to spot co-orbital companions when they are small or near the Lagrangian equilibrium points.

Ford & Gaudi [3] noticed that, contrarily to the case of a single planet in a circular orbit, if the planet that is transiting has a co-orbital companion located at one of its Lagrangian points, there is a time shift between the mid-transit and the mean radial-velocity, depending on the properties of the co-orbital companion. Therefore, when we combine transit and radial-velocity measurements, it is possible to infer the presence of a co-orbital companion. This method was developed for circular orbits and for a companion at the exact Lagrangian point (without libration). Although it remains valid for small libration amplitudes (which would just slightly modify the determined mass), co-orbital exoplanets can be stable for any amplitude of libration. Moreover, for a single transiting planet in a slightly eccentric orbit, we can also observe the same kind of time shift, without requiring the presence of a co-orbital companion.

Here, we generalise the work by Ford & Gaudi to eccentric planets in any Trojan or Horseshoe configuration (any libration amplitude). When a planet is simultaneously observed through the transit and radial-velocity techniques, we propose a simple method for detecting the presence of a co-orbital companion that relies on a single dimensionless parameter α which is proportional to the planets mass ratio. Therefore, when α is statistically different from zero, we have

a strong candidate to harbour a co-orbital companion and we get an estimation of its mass. We also discuss the possibility of false positive detections due to other effects.

This method is applied to archival radial velocity data of 46 close-in (orbital period smaller than 5 days) transiting planets (without detected companions) with information from high-precision radial velocity instruments. We identify 13 systems where the archival data provides at least 1σ evidence for a mass imbalance between L_4 and L_5 . Four of them provide more than 2σ detection, being the best candidates for subsequent follow-up observations.

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The capture rate of free-floating planets in our galaxy

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Abstract

Free-floating planets were detected through direct imaging and microlensing surveys. However, their population remains a mystery due to detection limitations of such faint objects. It was proposed that planetary nebulae and supernova remnants may constitute a significant source of free-floating planets, as many of them exhibit outflows of planetary-mass gas blobs. With a large population of free-floating planets, the rate at which these planets get captured by planetary systems may be non-negligible. To evaluate this rate, we constructed a three-dimensional scattering simulation between a free floating planet and a star accompanied by a Jupiter-mass bound planet. We tested different masses of the free floating planets and stars, impact parameters, inclination angles and approach velocities. With the use of the resulting capture statistics, we analytically approximated the cross section of such captures, and predict that about one out of every 100 sub-solar stars are expected to experience a capture of a free-floating planet during their lifetime.

1. Introduction

Observations of nearby supernova remnants and planetary nebulae revealed outflows of thousands of high-speed and planetary-mass gas blobs [2, 5, 6]. Some of these blobs may escape into the interstellar medium (ISM), where they cool and slow down by accretion of interstellar ambient matter, and collapse if their mass reaches the Jeans mass. As a source for free-floating planets, we may expect hundreds of them per cubic parsec in our galaxy, that were originated through this mechanism [1].

With a large population of free-floating planets wandering through the ISM, some may get captured by planetary systems, where they will not share the same characteristics that are inherited from the host star. Since free-floating planets can encounter planetary systems at different inclination angles, captured planets may explain a considerable fraction of the hot Jupiters whose orbital axis is misaligned with the spin

axis of their host star.

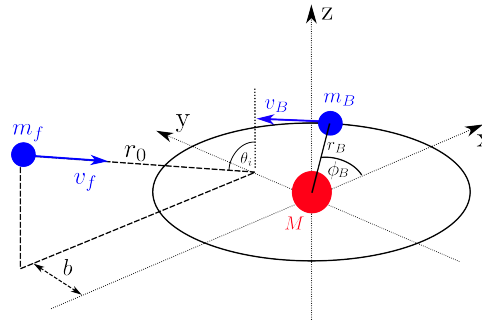


Figure 1: The scattering simulation involves a free floating planet m_f that approaches a star M accompanied by a Jupiter-mass bound planet m_B with a velocity v_f , inclination angle θ_i and impact parameter b . The bound planet orbits around the host star with a constant distance of r_B from the star.

2 Numerical Method

Our simulation is an extension of the work carried by Varvoglis et al. [7], which was restricted to coplanar scatterings. We included an unbound planet and star-planet binary, which are represented as point-mass objects. The free-floating planet approaches the binary with some initial velocity v_f and inclination angle θ_i , and interacts with a Jupiter-mass bound planet that is on a circular orbit of $r = r_B$ around the host star (see Fig 1). The dynamical system is described by a simple Lagrangian that includes the kinetic term of each body and the interaction terms between them,

$$\begin{aligned}\mathcal{L}_{kinetic} &= \frac{1}{2}m_f v_f^2 + \frac{1}{2}m_B v_B^2 \\ \mathcal{L}_{interaction} &= -G \frac{M m_f}{r_f} - G \frac{M m_B}{r_B} + G \frac{m_f m_B}{|\mathbf{r}_f - \mathbf{r}_B|}.\end{aligned}$$

Simulations are performed for different inclination angles, masses, and approach velocities. 175 values of

impact parameters (b) and 125 initial orbital phases of the bound planet (ϕ_B) are tested; a total of 21,700 runs for each simulation. Once the free-floater travels out approximately twice its initial distance from the star, the simulation stops, and the total energy of the free-floating planet (E_f) and the bound planet (E_b) is calculated. Captures ($E_f < 0, E_B < 0$), flybys ($E_f > 0, E_B < 0$) and exchange ($E_f < 0, E_B > 0$) are distinguished.

3 Results

The fraction of simulation runs that led to a capture (Fig 2), as a function of inclination angle, masses and the approach velocity, is used to construct an analytical approximation of the cross section. As received by Varvoglis et al. [7], about 50% of the coplanar simulation runs led to captures. This percentage drops as the approach velocity becomes higher and less aligned with the orbital plane of the bound planet.

Using our analytically approximated cross section, and assuming the predicted number densities of free-floating planets that originated from explosive death of stars, we evaluate that a capture will occur every ~ 200 years in our galaxy. Since low-mass stars have a longer lifetime and dominate the stellar population, most of the captures are expected to involve such stars. We estimate that $\sim 1\%$ of all $0.1M_\odot < M < 2M_\odot$ stars are expected to experience a capture during their lifetime.

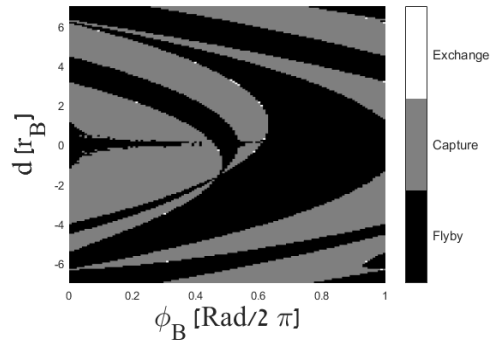


Figure 2: The outcomes of a coplanar scattering simulation between a Jupiter-mass free-floating and bound planets, and a solar-mass host star. Pixels correspond to different values of impact parameters of the free-floating planet and orbital phases of the bound planet.

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Pebble pile-up and planetesimal formation at the snow line

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Abstract

The planetesimal formation stage represents a major gap in our understanding of planet formation process. Because of this, the late-stage planet accretion models typically make arbitrary assumptions about planetesimals and pebbles distribution, while the state-of-the-art dust evolution models predict no or little planetesimal formation. With this contribution, I present a step toward bridging the gap between the early and late stages of planet formation by models that connect dust coagulation and planetesimal formation. With the aid of evaporation, outward diffusion, and re-condensation of water vapor, pile-up of large pebbles is formed outside of the snow line that facilitates planetesimal formation by streaming instability.

1. Introduction

Our understanding of planet formation is limited by the disconnection between its early and late stages. This is because the growth barriers: the dust growth is inhibited at centimeter sizes and some particular conditions are needed for the formation of larger, gravitationally bound planetesimals and planetary embryos [1]. We cannot really explain how and where planetary embryos form. As a consequence, models that deal with the late-stage planet accretion, when a planetary embryo grows to its final size and structure, typically use the same input models for the radial distribution of gas and solids as the early-stage models dealing with dust growth and planetesimal formation, which is obviously inconsistent.

Probably the most widely accepted planetesimal formation scenario at the moment is called the streaming instability. It leads to formation of dense filaments of pebbles that subsequently become gravitationally unstable and collapse to planetesimals. This scenario allows us to bypass the fragmentation barrier and form gravitationally bound object directly from cm-sized pebbles that can be obtain from dust coagulation.

In a realistic disk conditions needed by the streaming instability (which include existence of large peb-

bles and high dust-to-gas ratio) are not easily met. Such disks typically start their evolution with dust-to-gas ratio of 1%, which gets lower because of removal of solids by the radial drift. Dust pile-ups are necessary to allow for planetesimal formation in gas-rich phase of protoplanetary disk [2] while disk dispersal may allow for late planetesimal formation [3]. Both of these processes may be needed to explain the existence of different types of planets and debris belts, for instance in the Solar System.

2. Models

I developed one dimensional model for evolution of protoplanetary disk that includes:

- gas disk evolution: I tested several different models, both with and without stellar irradiation, obtaining qualitatively similar results; the non-irradiated models are based on the work of [4] and the irradiated models on [5];
- dust growth, fragmentation, and radial drift: the dust evolution model closely follows the algorithm proposed by [6]. This algorithm was designed to reproduce full dust growth simulations at much lower computational expense. One significant modification is that the so-called collective drift effect is considered, which means that the radial drift velocity decreases with increasing dust-to-gas ratio;
- evaporation, diffusion, and re-condensation of water following treatment proposed by [7];
- planetesimal formation via streaming instability using semi-analytical prescription similar to [8].

3. Results

Processes happening around the snow line facilitate planetesimal formation via streaming instability. Ice evaporation and outward diffusion of water followed by its re-condensation increases abundance of icy pebbles that triggers planetesimal formation just outside

of the snow line. Typical evolution in an irradiated protoplanetary disk is showed in Fig. 1. An annulus of planetesimals is formed between 2 and 10 au. The total mass of these planetesimals is over $100 M_{\oplus}$. For the non-irradiated disk models, the snow line typically falls closer to the central star and thus the inner edge of planetesimal belt is shifted inwards.

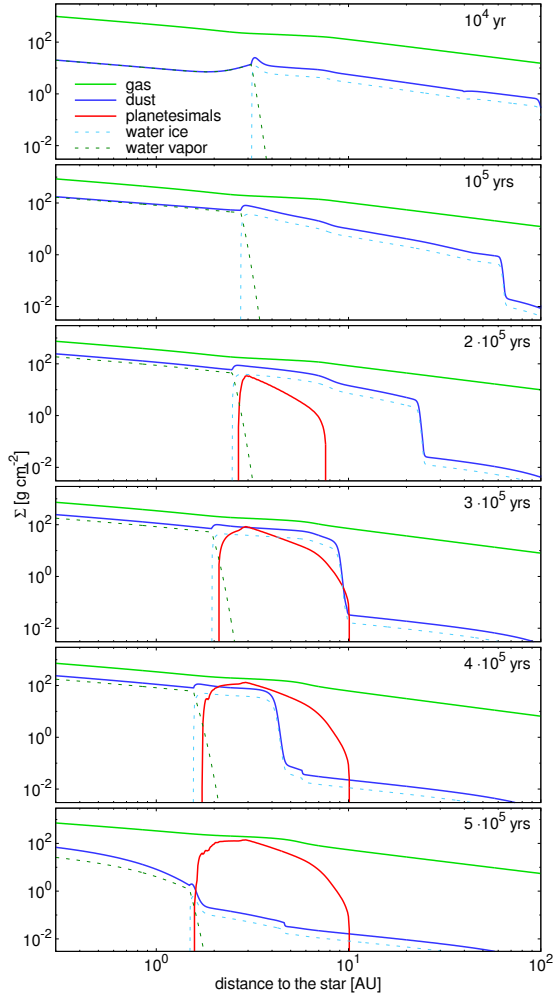


Figure 1: Temporal evolution of gas (green solid line), dust (blue solid line), and planetesimals (red solid line) surface densities radial distribution. Water ice and vapor contributions are also showed with the dashed lines.

4. Summary and Conclusions

This contribution addresses the connection between dust growth and planetesimal formation, which corresponds to a major gap in the state-of-the-art planet for-

mation models. Planetesimal formation is possible in a smooth protoplanetary disk thanks to the pile-up of icy pebbles outside of the water snow line. This massive annulus of planetesimals will trigger formation of planetary embryos that can benefit from the high surface densities of both planetesimals and pebbles.

Acknowledgements

The author is supported by the PlanetS National Center of Competence in Research (NCCR), which is a research instrument of the Swiss National Science Foundation.

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Element fractionation in the early solar system: The role of nebular captured H₂-envelopes

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Abstract

The composition of the solar nebula, in which proto-Earth and proto-Venus formed, can be derived by the analysis of different families of chondrites. Compositional variations between those chondrites and the chemical abundances of the terrestrial planets provide evidence that some sort of elemental and isotopic fractionation should have taken place early in the history of the solar system. Some of those fractionations can be explained via atmospheric loss [1] and the collisional erosion of the early differentiated crust [2], whereas others remained poorly understood. An additional mechanism for the early fractionation of elements and isotopes at the terrestrial planets will thus be described for the first time within this presentation.

1. Introduction

During the disk-embedded phase, early in the evolutionary history of the solar system, protoplanetary cores are believed to accumulate hydrogen gas and to form thin planetary H₂-envelopes. According to the “Grant-Tack” scenario [3], those protoplanetary cores (proto-Earth and proto-Venus) should have accumulated a size of 0.5-0.75 Earth- and Venus-masses, respectively until the solar nebular evaporated and a short H₂-“boil-off” phase should have taken place. After the evaporation of the solar nebula, the accumulated H₂-atmosphere contracted and EUV-driven hydrodynamic escape started to slowly erode the H₂-envelope. In addition, constant bombardment of impacting material, delivered further material to growing proto-Earth and -Venus. Most of this impacting material got evaporated due to high impact velocities and the high pressure-related temperature of the H₂-envelope. This presentation shows how the evaporated material can be dragged away via hydrodynamic escape, adding up to the observed elemental and isotopical fractionation at the terrestrial planets.

2. Fractionation of K, ³⁶Ar, ²⁰Ne and others

Lighter elements, such as potassium (K) compared to uranium (U), as well as isotopes, as for example ³⁶Ar compared to ³⁸Ar, or ²⁰Ne compared to ²²Ne can escape easier from proto-Earth and proto-Venus due to H-drag from a nebula-captures H₂-envelope compared to a magma ocean related outgassed steam atmosphere, whereas heavier elements and isotopes cannot be dragged away that easily. Our simulations of this fractionation phase show that this effect can explain some of the initial compositional variations between the terrestrial planets and the original solar nebula as derived via data from chondrites. Our solutions of these nebula based fractionations are also supporting the Grant-Tack scenario.

Acknowledgements

The authors acknowledge the support of the FWF NFN project S11601-N16 “Pathways to Habitability: From Disks to Active Stars, Planets and Life”, in particular the related subprojects S11604-N16 S11606-N16, and S11607-N16. The authors also acknowledge the FWF project P25256-N27.

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Forming compact planetary systems via type I migration

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Abstract

Of the myriad of insights into exoplanetary systems provided by the Kepler mission, one of the most intriguing new discoveries is that of a class of compact planetary systems which include Kepler-11 and Kepler-90. In such systems, ensembles of several planets are found in very closely packed orbits (often within a few percent of an astronomical unit of one another). These systems present a challenge for traditional formation and migration scenarios, since these planets presumably formed at larger orbital radii before migrating inwards. In particular, it is difficult to understand how some planets in such systems could have migrated across strong mean-motion resonances without becoming trapped. It is also difficult to explain how such systems remain dynamically cold, as resonant interactions tend to excite orbital eccentricity and lead to close encounters. Using both N-body models and two dimensional hydrodynamical simulations, I explore this problem in detail, and show that under the right conditions, super Earths can indeed migrate through mean-motion resonances [1]. I demonstrate that systems with giant outer planets such as Kepler-90 are more likely to exhibit tighter resonances [2], and that interactions with the protoplanetary disc itself can lead to the breakdown of otherwise-stable resonances [3].

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Importance of the early accretion stage of a protoplanetary disk on the chemical evolution of planetesimals and comets

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Abstract

Chemical evolution of a protoplanetary disk has been studied with a model combining dust transportation and chemical equilibrium of condensed matters. The results show that the initial size and mass of a disk strongly control the temperature evolution, thus chemical evolution of the disk. Assuming that chondrites are derived from planetesimals formed at a few to several a.u. and comets were formed at tens of a.u., the initial size of our solar system was less than 0.1 solar mass and spread to ~tens of a.u. in order to explain chemical variations of chondrites and recent observation of comprehensive inclusion of high-temperature condensates in comets.

1. Introduction

Recent ALMA observation has shown various features of protoplanetary disks, such as a ringed structure [1], gaps suggestive of formation of large planets [2], spiral arms [3], dust/gas/star mass relationships [e.g. 4, 5], a change of gas chemistry in the envelope [6], or possibility of the location of the snow-line [7], all of which suggest active and evolving protoplanetary disks. A few studies that reveal the age and sizes of central stars and surrounding disks show clear negative relationships between age and disk mass regardless of the size of the central stars.

However, more detailed information cannot be obtained with ALMA, and the information on our solar system is still critical in order to understand the evolution of protoplanetary disks. Because the critical information is taken from exploration and sample analysis of meteorites and comets, chemistry and mineralogical information are the critical ones, and therefore, physical and chemical evolution of protoplanetary disks should be considered consistently with meteorite and cometary material information including Rosetta and Stardust missions.

2. Model

We have developed a model that describes the chemical evolution of protoplanetary disks, which is basically a radial advection-diffusion equation written in the Cartesian coordinate originally developed by Ciesla [8,9]. The key of the model is that the equation is written in the Lagrangian expression, which enables us to trace movement of individual dust particles that experience different thermal histories in the protoplanetary disk due to advection and turbulent flows. We call the method “particle tracking method”. Chemical information is shown by equilibrium chemistry for individual grains according to the initial density and temperature conditions of the disk, which varies depending on the initial disk size discussing below.

The model contains two free parameters: initial disk mass and initial disk size, both of which control the temperature profile of the disk and time scale of dust transportation and temperature evolution.

The disk is a viscous disk with the parameter, α , and the initial disk mass and size determine the density and temperature distribution. Dust particles are assumed to be 1 micron in size, and we neither consider accretion to the disk nor dust coagulation. The dusts are chemically in equilibrium with ambient gas at the initial conditions. Silicate and metal-sulfide grains are assumed to keep the initial chemical compositions and organics and ice are assumed to evaporate according to the disk conditions.

Ten thousands of grains are set in more than 20 separated bins of the disk and the movement of the grains are traced for a million years. Chemical composition of a certain area and certain time of the disk is calculated by summing up all the grains with different histories that are present in the region at the time. Particular attention has been paid for high-temperature condensates and organics and ice grains.

3. Results

Temporal and spatial distribution of chemical composition of protoplanetary disks with various initial disk parameters was obtained. The important results are: (1) the initial temperature profile is strongly dependent on the initial disk size, the silicate evaporating region extends to ~ 1 au if the disk mass is 0.1 solar mass, but ~ 10 au for 1 solar mass, (2) considerable amounts of dust particles initially located in the inner region are transported to the outer region, which continues for more than a million years although the absolute amount of such grains decreases significantly, and the outer edge where the grains from the inner region reach strongly depends on the initial disk mass and size, (3) chemical composition of a certain region varies significantly with time due to mixing of chemically highly fractionated materials from the inner region and unfractionated materials from the outer region, (4) chemical composition of chondrites, specifically those of carbonaceous chondrites, are reproduced with a limited range of initial disk conditions if they were formed at the asteroid belt as they are now, which is possible when the initial disk size is smaller than several au, (5) a protoplanetary disk becomes chemically highly homogeneous with unfractionated chemical composition, that is, the solar abundance elemental ratios, which is the case for smaller and/or lighter initial disk, and (6) mixing ratio of H₂O ice and silicates originated at the inner region is strongly dependent on the initial disk mass and size. Figure 1 shows the fraction of solid materials along the midplane of a protoplanetary disk for initially small (10au) disk (a and b) and largely extended (100au) disk with the same mass (c and d), where the disk initial mass is the same for all the cases (0.05 solar mass). The initially small disk (a and b) results in highly depleted in H₂O ice in the outer region, and silicates are much more abundant than H₂O ice after a million year (Fig. 1b). On the other hand, largely extended disk results in H₂O-ice enriched materials after ten thousand years (Fig. 1c) or later (Fig. 1d).

4. Discussions and conclusions

Comprehensive presence of high-temperature condensates in comets requires mixing of outward transported grains with a considerable amount of H₂O ice beyond tens of au, which is possible for a disk with the initial mass of ~ 0.1 solar mass and the initial spread to tens of au. On the other hand, this condition results in almost homogeneous chemical

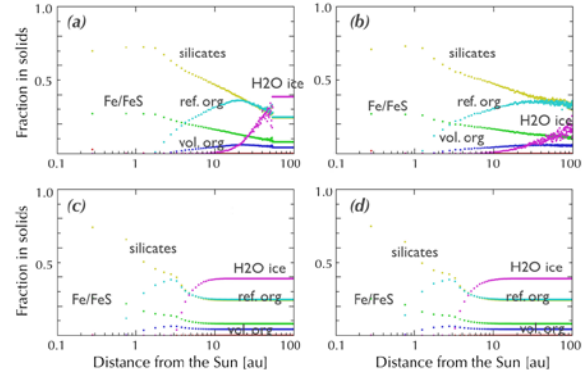


Figure 1: Temporal and spatial distribution of silicates and Fe-FeS transported from the inner region outward and H₂O ice and organics transported from the outer region inward. (a) Initial disk mass=0.05 solar mass and the initial disk radius=10 au after 10^5 yrs, (b) 10^6 yrs, (c) initial disk mass=0.05 solar mass and initial disk radius=100 au after 10^5 yrs, and (d) 10^6 yrs.

composition in the asteroid belt region. The chemically fractionated compositions of chondrites in terms of volatile element depletion can be achieved at the early stage (earlier than 10^5 yrs). The present study predicts the importance of the initial conditions of the protoplanetary disk for its chemical evolution; in other words, planetary system chemistry is highly related to the star formation.

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The part of the core in thermal evolution of super-Earths

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Abstract

Standard planet evolution models of super-Earths assume that the terrestrial part (hereafter core) is cooling as fast as the envelope. But several works show that core heat transport may be much slower [1]. Slow core cooling by conduction and/or high-viscosity convection, leads to a cooling timescale of billions of years, which overlaps with the regime of super-Earth observation data. In addition, it can become dependent on initial conditions.

We calculate the thermal evolution of the core simultaneously with the evolution of the envelope. We find that planet formation history and core thermal evolution can have a substantial and long term effect on planet radius and cannot be neglected in evolutionary calculations of super-Earth planets. We present the contribution of this effects to the mass-radius relation of super-Earth, and the implications on the interpretation of observation data.

1. Introduction

Although we don't have such planets in our own solar system, super-Earths are the most abundant class of planets known to date in our galaxy. Those planets exhibit a great diversity in their mass-radius relation. Most studies attempt to relate this diversity to composition, but the thermal evolution of the planet can play a key role in this diversity. In contrast to other planet types, in super-Earths the core is the dominant energy reservoir, while the gaseous envelope, which is very sensitive to thermal conditions, determines the planet's radius. Thus, the cooling rate of the core, which contains great uncertainties, affects the radius of the planet in time.

2. Model

We employ a complete center-to-surface 1D evolutionary model of super-Earth planets, in which the solid core and a gaseous envelope share the same structure grid. The energy transport is by convection, conduc-

tion or radiation, depends on the local conditions and composition in each layer, as described in [3]. We use a realistic equation of state and proper opacity tables [2], and solve the structure and evolution equations for the entire planet in an adaptive grid with variable time step.

3. Results

We find that the influence of the core thermal evolution on the envelope radius can be substantial (tens of percent) and depends strongly on thermal parameters, as shown in table 1.

Parameter (range)	Radius (%)
Initial envelope radius ($0.1-1 R_{\text{Hill}}$)	5%
Core composition (rock/ice)	5%
Radioactive heating ($0-E_{\oplus}$)	10%
Core heat transport rate (conv-cond)	40%
Initial core temperatures ($0.05-0.2 E_{\text{acc}}$)	25%
Age (1-10 Gyr)	50%
Envelope mass (1-10% of M_p)	100%
Atmospheric opacity ($\text{ESN} - \text{ESN}/10$)	20%

Table 1: Ranges of thermal evolution parameters that were examined (left) and their effect on the planet radius (right) for super-Earth planet masses.

The effect of the heat transport rate within the core on the radius evolution is significant. In figure 1 we present two planets which are identical in structure, composition and initial conditions. The heat transport within the core in one planet is by large-scale convection (green), as used in standard models [4], and in the second planet is by slow convection and conduction (black) as recent works suggest [5]. For the slow core cooling case the luminosity of the core (dashed dotted) determines the planet luminosity (solid) on Gyr timescale. As a result, the radius of this planet is larger, over long period of time.

The temperature profile evolution for the two cases is shown in figure 2. The less efficient heat transport in the slow cooling core, as well as in the core-envelope

boundary, result in much hotter core -than the standard model- on Gyrs timescale.

The influence of the different thermal properties (see table 1) on the mass-radius relation of super-Earth is presented in figure 3. As shown, such a model can explain the few observed super-puffs planets with much less gas content than is usually assumed.

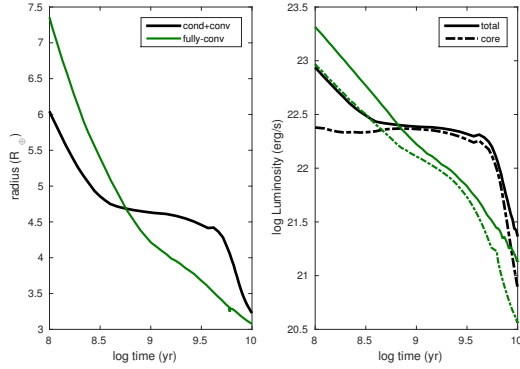


Figure 1: Radius (left) and luminosity (right) evolution of $5 M_{\oplus}$ planets with 10% of the mass in H+He envelope. The heat transport within the core is by large-scale convection (green) and by slow convection and conduction (black).

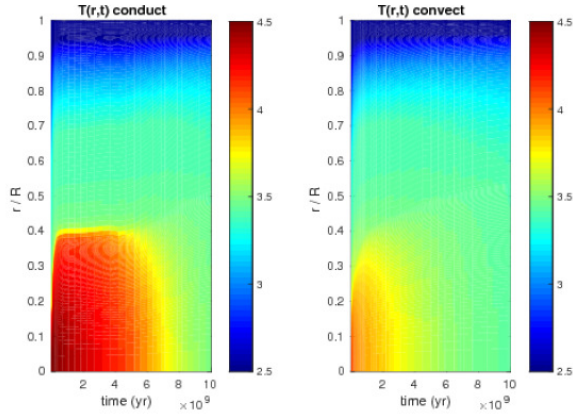


Figure 2: Temperature profile evolution for the two cases of figure 1: slow (left) and fast (right) heat transport in the core. The temperature (color) in log scale is presented as function of radius (y-axis) and time (x-axis).

4. Conclusions

1. Super-Earths are more sensitive to thermal processes (formation and evolution) than other planetary types, because of the high core to envelope ratio.
2. The mean density diversity of super-Earths is not determined only by composition (*i.e.*, hydrogen and helium fraction), but can also be driven by different thermal conditions and evolution, as shown in figure 3.
3. The uncertainties in thermal parameters should be considered when inferring the composition from observed mass-radius pairs of super-Earths.

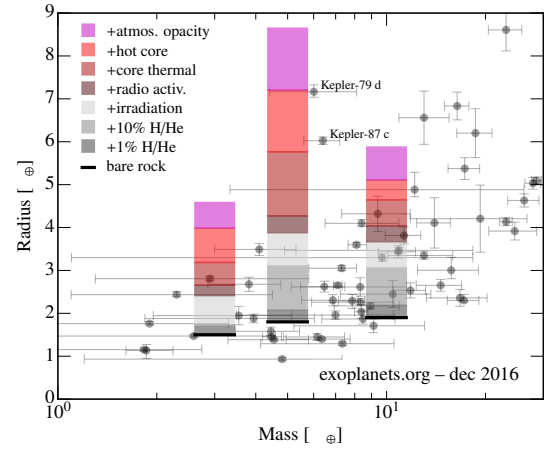


Figure 3: Cumulative contributions of structure and thermal evolution properties (see table 1) on the mass-radius relation of super-Earth planets. Each colored block indicates the maximum change in radius obtained from a single effect within 1-10 Gyr timescale.

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