Formation of planets by tidal downsizing of giant planet embryos

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ABSTRACT

We hypothesize that planets are made by tidal downsizing of migrating giant planet embryos. The proposed scheme for planet formation consists of these steps: (i) a massive young protoplanetary disc fragments at \( R \sim \) several tens to hundreds of au on gaseous clumps with masses of a few Jupiter masses; (ii) the clumps cool and contract, and simultaneously migrate closer in to the parent star; (iii) as earlier suggested by Boss, dust sediments inside the gas clumps to form terrestrial mass solid cores; (iv) if the solid core becomes more massive than \( \sim 10 \, M_J \), a massive gas atmosphere collapses on to the solid core and (v) when the gas clumps reach the inner few au from the star, tidal shear and evaporation due to stellar irradiation peel off the outer metal-poor envelope of the clump. If tidal disruption occurs quickly, while the system is still in stage (iii), a terrestrial planet core is left. If it happens later, in stage (iv), a metal-rich gas giant planet with a solid core emerges from the envelope.

Key words: planets and satellites: formation – stars: formation.

1 INTRODUCTION

There are currently two competing theories for planet formation in which the planet-making action starts from opposite ends. The core accretion (CA) model (e.g. see Safronov 1969; Pollack et al. 1996; Ida & Lin 2008, and chapters 4–6 in Armitage 2010) stipulates that planets form in a bottom-up scenario. First, microscopic dust in the protoplanetary disc grows into grains. There is then a poorly understood but necessary step (e.g. Wetherill 1990) of grains joining up somehow (see Youdin & Goodman 2005; Johansen et al. 2007) to make kilometre-sized objects (planetesimals), which then collide and stick to form ever larger solids up to terrestrial planet masses. When the solid core reaches a critical mass of about \( 10 \, M_J \), a massive gas envelope builds up by accretion of gas from the disc.

In contrast, the gravitational instability (GI) model suggests that giant planets form ‘big’, e.g. directly by contraction of gaseous condensations born in a massive self-gravitating disc (e.g. Bodenheimer 1974; Boss 1997). Giant planets in the Solar system contain massive solid cores (Fortney & Nettelmann 2009), as predicted by the CA model. In the context of GI, Boss (1998) suggested that such cores could result from dust sedimentation inside gaseous protoplanets. Boss, Wetherill & Haghighipour (2002) showed that removal of the gas envelope by photoionization due to a nearby OB star could make the ice giants of the Solar system.

Of these two models, the GI is the one that received the lion’s share of the criticism. The most notable problems of the model are (a) protoplanetary discs cannot form giant planet embryos at the location of Jupiter (e.g. Rafikov 2005) contrary to earlier results by Boss (1997); (b) Helled & Schubert (2008) and Helled, Podolak & Kovetz (2008) found that dust sedimentation is too slow a process to yield observed solid cores in giant embryos of mass \( \lesssim \) Jupiter’s mass; (c) OB stars are too rare to explain the abundance of Jupiter-like planets observed in extrasolar planetary systems and (d) there seems to be no way to form terrestrial planets like the Earth.

The goal of this Letter is to show that this criticism has long outlived itself. All of the points raised above can be addressed if one upgrades the 1990s version of the GI model with more modern ideas – formation of giant planet embryos (GEs) far from the parent star where the process is allowed (Rafikov 2005), and then letting them migrate radially inwards, as massive planets do (Goldreich & Tremaine 1980).

We have recently revisited (Nayakshin 2010a, hereafter Paper I) the suggestions of Boss (1998) and Boss et al. (2002) on dust sedimentation in GEs assuming that they are formed at \( R_p \sim 100 \, \text{au} \). Such GEs are cooler by an order of magnitude than those studied by Helled and co-authors. GEs with masses below about \( 10–20 \) Jupiter masses (\( M_J \)) are found (Nayakshin 2010b, hereafter Paper II) to be excellent sites of solid core formation. Thus addressing point (a) addresses point (b) automatically.

Below we estimate the migration time of the embryos in a realistic young massive protoplanetary disc. We note that as embryos migrate closer to the parent star, their Hill’s radius decreases faster than they can shrink due to internal cooling. When these two are equal, we assume that the GE can be disrupted by the tidal field of the star, which normally occurs at a few au distance. However, we find that grain sedimentation time is shorter than the migration time for plausible parameter values. Thus, by the time the embryos are due to be disrupted, they may already contain massive solid cores. Depending on the properties of the GE at disruption, removal of...
the outer metal-poor gas shell reveals either a terrestrial planet or a metal-rich giant planet. We therefore argue that such a ‘tidal downsizing’ scheme may explain planets of all types without recourse to planetesimals (Safronov 1969; Wetherill 1990).

Our hypothesis is a hybrid scenario: giant planet formation starts with dust sedimentation inside a self-gravitating gas clump (Boss 1998), as in the GI model, but continues as in the CA model with accretion of a massive metal-rich gas envelope from within the GE. Additionally, solid cores left by the GE disruption in the protoplanetary disc may grow further like in the CA model – by accreting smaller solid debris from the disc. Giant planets may accrete more gas and also migrate radially, as in the ‘standard theory’.

2 GIANT PLANET EMBRYO MODEL

2.1 Birth and contraction

Massive young gas discs are gravitationally unstable and fragment on clumps when the disc-cooling time is no longer than a few times the local dynamical time, 1/Ω (e.g. Gammie 2001), whereΩ = (GM∗/R3)1/2 is the Keplerian angular frequency at radius Rp from the star of mass M∗. This limits the fragmentation region to Rp ≥ 30–100 au (e.g. Rafikov 2005; Stamatellos & Whitworth 2008; Meru & Bate 2010). At the point of marginal gravitational stability the density in the disc mid-plane is about the tidal density at that point, ρ1 = M∗/(2πRp). Thus, when the disc just fragments, the disc-cooling time is about the free-fall time-scale for the material in the disc, tf = 1/√ΩG. As the clumps contract further, their cooling time becomes longer than their free-fall times. The initial state of the local dynamical time, 1/Ω.

Additionally, solid cores left by the GE disruption in the protoplanetary disc may grow further like in the CA model – by accreting a massive metal-rich gas envelope from within the GE.

Note that the cooling time of the embryo increases with time, so that tcool decrease with time as tf = t0 + 2f

2.2 Dust growth and sedimentation

We echo the approach of Boss (1998) here; the resulting grain-growth time-scale in a constant density embryo, for a grain with initial size a0 to reach the final size a is

\[ t_{gr,0} = \frac{3c_s}{\pi f_0 \rho_0 G R_0} \ln \frac{a}{a_0}, \]  

where \( \rho_0 = 3M_{emb}/4\pi R_0^3 \), \( c_s \) and \( f_0 \approx 0.01 \) are the initial embryo mean density, the sound speed and the grain fraction by mass, respectively. In Paper I we improved on this model by allowing the embryo to contract, in which case the growth time is a geometric combination of the cooling and the initial grain growth time, \( t_{gr} = t_{gr,0} t_{vap} \).

\[ t_{vap} = 3 \times 10^3 \text{ yr} m_{9/3}^{-2/7} f_{-2}^{-4/7} k_{s}^{2/7} \left( \frac{\ln(a/a_0)}{20} \right)^{4/7}, \]

where \( f_{-2} = f_0/0.01 \). The vaporization time, \( t_{vap} \), is the time it takes for the embryo to heat up to the vaporization temperature of \( T_{vap} = 1400 \text{ K} \). This is trivially obtained by solving the equation \( T(t_{vap}) = T_{vap} \) (using equation 1), and a good approximation is

\[ t_{vap} = 1.5 \times 10^4 \text{ yr} \left( \frac{T_{vap}}{1400 \text{ K}} \right)^2 m_{9/3}^{-2} k_{s}. \]

Grains sediment to the centre of the core when \( t_{gr} < t_{vap} \), and vaporize before they could sediment if \( t_{gr} > t_{vap} \). The mass of refractory material (e.g. silicates) that can be used to build a massive core is expected to be about one-third of the total heavy elements mass, or about 20 M⊕ for \( M_{emb} = 10M_\oplus \) (Boss et al. 2002). However, due to energy release associated with the solid CA, strong convective motions near the core may develop. The grains also melt at too high CA rates. Thus the final mass of the core is usually much smaller than the maximum condensable mass (Paper II).

2.3 Radial migration of embryos

Gravitational torques between the disc and massive planets are significant (e.g. Goldreich & Tremaine 1980; Tanaka, Takeuchi & Ward 2002). While GEs are smaller than their Hill’s radii (see below), we assume that they migrate at similar rates. Under this assumption, embryos migrate via type I regime if \( M_{emb} \leq M_t = 2M_\star (H/R)^2 \) and via type II regime if \( M_{emb} > M_t \), where \( M_t \) is the transition mass (Bate, Bonnell & Bromm 2003). For a self-gravitating, Q = 1 disc, the type II migration time is

\[ t_1(R_p) = \frac{R_p}{M_{emb}} H \sqrt{\frac{H}{R_p}} = 4 \times 10^3 \text{ yr} \frac{R_p^{3/2}}{\sqrt{H}} \left( \frac{0.2R_p}{H} \right)^2, \]

where \( \alpha_{-1} = \alpha/0.1 \) is the disc viscosity parameter and \( R_2 = R_p/100 \text{ au} \). Type I migration is faster:

\[ t_1(R_p) = \Omega^{-1} \frac{M_\star}{M_{emb}} \frac{H}{R_p} = 3 \times 10^3 \text{ yr} \frac{R_p^{3/2}}{\sqrt{H}} \frac{H}{0.2R_1} \]

We can improve these estimates by building a simple disc model that would specify how disc properties change with R. We define the stellar mass doubling time-scale as \( t_{db} = M_t/M_\star \), where \( M_t \) is the mass accretion rate on the star, assumed to be constant in time and radius inside the disc. By the order of magnitude, \( t_{db} \) should be comparable to the free-fall time of the host gaseous cloud from which the star forms, e.g. \( \sim 10^6 \text{ yr} \) for a 1 M⊙ cloud at the typical interstellar temperature of 10 K (e.g. Larson 1969).

Using the standard Shakura & Sunyaev (1973) accretion disc formalism, we first find \( H(R) \) and \( M_d(R) \) in the innermost disc. We then find the radius beyond which the Toomre (1964) parameter falls below unity. In the outer self-gravitating region of the disc we follow the treatment of Goodman (2003) for a disc with no internal...
energy sources and enforce \( Q \approx (H/R)(M_e/M_0) = 1 \). Finally, for a constant accretion rate disc, \( M = 3\pi\alpha H^2\Omega \Sigma_d \), where \( \Sigma_d \approx M_d/R^3 \) is the column depth of the disc, we can solve for

\[
\frac{H}{R} = \left[ \frac{1}{3\alpha\Omega_{\text{emb}}} \right]^{1/3}. \tag{10}
\]

The accretion rate disc model built in this way is schematic but correctly predicts the expected location of the self-gravitational region at \( R_e > \text{few tens of au to 100 au} \). Using this disc model we are now able to calculate the migration rate of a GE at an arbitrary \( R_e \) for a given \( t_{\text{gb}} \). We follow the fit to numerical results by Bate et al. (2003) to smoothly join the type I and type II migration regimes. The fastest migration then occurs for embryo mass \( M_{\text{emb}} = M_1 \).

### 2.4 Tidal disruption

The Hill’s radius of the embryo is (for \( M_e = 1 M_\odot \))

\[
R_H = R_p \left[ \frac{M_{\text{emb}}}{3M_e} \right]^{1/3} = 0.15 R_p m_1^{1/3}. \tag{11}
\]

In general, radial migration accelerates as the GE moves in, whereas the contraction of the envelope slows down with time (cf. equation 4). Therefore, as planets migrate inwards, there is a point where the embryo’s radius \( R_{\text{emb}} \) becomes comparable to the GE Hill’s radius. The tidal field from the parent star at this point starts to peel off the outer layers of the embryo. The tidal radius, \( R_t \), is defined as the radius where \( R_{\text{emb}} = \eta_1 R_t (\eta_1 \lesssim 1) \). Using the type II migration estimate as an example, we insert equation (8) into equation (4), and find

\[
R_t = 2.8 \text{ au } \eta_1^{-1/2} R_2^{3/4} R_e^{1/2} \frac{H}{0.2R_m} m_1^{-1/3}. \tag{12}
\]

In Appendix A we show that irradiation by the parent star can heat up the outer layers of the envelope and even disrupt the whole GE. The effect appears less important than tidal disruption for solar type stars, but may become dominant for higher mass stars.

### 3 An illustrative example

Fig. 1 shows the results of our giant embryo model described in Section 2 for embryos of 3, 6 and 10 \( M_1 \), shown with different colours. The parameters used for the figure are \( t_{\text{gb}} = 10^5 \text{ yr} \), \( \alpha = 0.1 \), \( \kappa_0 = 0.01, M_e = 0.5 M_\odot \) (as the star is assumed to be in the midst of its growth, rather than close to being completely assembled), solar metallicity, and the starting radial position is \( R_p = 100 \text{ au} \).

The upper panel shows radial migration of the embryos. Note that initially all migrate at about the same rate (in the type II regime), but then the least massive embryo overtakes the others two. The least massive one (black solid curves) migrates the fastest as it happens to fall in the minimum of the migration time curve, between type I and type II regimes (see fig. 11 in Bate et al. 2003). The asterisks and the text ‘core formation’ mark the time \( t = t_{\text{gb}} \), when the solid core is assumed to form in the centre of the GEs (cf. equation 6).

The middle panel shows the embryo size, \( R_{\text{emb}} \), and the respective Hill’s radius, for the three cases considered. We assume that when the two sets of curves intersect, the embryo is disrupted, leaving only the core, which migrates at a negligible rate during the calculation. This is why the radial position curves, \( R_p(t) \), approach a constant value in the upper panel at late times.

The lower panel shows the respective temperature evolution of the embryos (cf. equation 1). The least massive embryo forms the core last, as it is the least dense of the three. However, it is also the coolest one. Due to this, the least massive embryos may lock most of their ‘metal’ content into grains and actually yield heavier solid cores (see Paper II). On the other hand, the least massive embryo is disrupted sooner (in accord with equation 12), at \( R_p \approx 6 \text{ au} \).

### 4 The tidal downsizing hypothesis

#### 4.1 Planets: leftovers of disrupted GEs?

We found that for plausible conditions, the GE initial cooling time, the dust growth time, the grain vaporization time and the GE migration time are related by

\[
t_0 \ll t_\text{gb} \ll t_{\text{mig}} \approx t_{\text{vap}}, \tag{13}
\]

\( t_0 \) days, \( t_\text{gb} \) years, \( t_{\text{mig}} \) years, \( t_{\text{vap}} \) years.
respectively. This order of time-scales implies that (1) the GE contracts quickly initially, which protects it from an immediate tidal disruption at the point where it is born; (2) grains have enough time to grow and sediment to the centre of the GE, forming a massive solid core there and (3) since the cooling time becomes asymptotically long (Section 2.1), the embryo is tidally disrupted at the inner few au.

4.1.1 Terrestrial planets

If the migration time is shorter than the vaporization time,

\[ t_{\text{migr}} < t_{\text{vap}}, \]

and the solid core mass, \( M_{\text{core}} \), is smaller than the critical core mass, \( M_{\text{cr}} \sim 10 \, M_\oplus \) (see below), the gaseous component of the GE is almost completely disrupted, e.g. disassociated from the solid core. As the density of the solid cores is a few g cm\(^{-3}\), almost completely disrupted, e.g. disassociated from the solid core.

4.1.2 Giant planets with solid cores

In Paper II we argued that when the solid core grows more massive than a critical core mass, \( M_{\text{cr}} \), the atmosphere near the core becomes so dense that it is gravitationally unstable and starts to collapse on the solid core. This ‘core-assisted’ collapse is quite similar to that found in the classical CA model (e.g. Mizuno 1980; Pollack et al. 1996), except that gas is accreted on the core from the GE rather than the disc. A proper numerical calculation is required to find the exact value of the critical mass, \( M_{\text{cr}} \), but much of which may be lost thereafter.

4.1.3 Giant planets without solid cores?

The GE may go through the second wave of collapse when the temperature reaches about 2000–2500 K (Larson 1969; Bodenheimer 1974; Masunaga & Inutsuka 2000) which can compact the gas component to densities as high as \( \sim 10^3 \, \text{g cm}^{-3} \). The time to reach that temperature is at least a few times the vaporization time (cf. equation 7). Therefore, if

\[ t_{\text{vap}} \gg t_{\text{vap}}, \]

then the giant embryo may collapse as a whole. Detailed calculations of this process in the planet formation context (e.g. Bodenheimer 1974) show that a Jupiter mass embryo only collapses in this way after \( \sim 10^7 \, \text{yr} \), which appears longer than the migration time for ‘reasonable’ parameters. However, more massive embryos start off hotter and should reach the second collapse stage sooner (see Paper II). Thus it is possible that giant planets more massive than Jupiter may have no solid cores.

5 ASTROPHYSICAL IMPLICATIONS

5.1 When does planet formation stop?

The view advanced in Sections 4.1.1 and 4.1.3 is an extreme version of the tidal downsizing hypothesis, where everything ‘interesting’ occurs inside the GEs before they are disrupted. This scenario is unlikely to be realistic. When the GEs are dispersed, their remnants are still embedded in a protoplanetary disc. The disc may be less massive, but as observations show it may persist for a few million years. Therefore, it is likely that the planet-building action continues at that stage, now in the CA model – solid cores may grow further by accreting smaller solid debris; giant planets may accrete more gas and also migrate radially. Therefore, the most reasonable point of view is that the tidal downsizing hypothesis, if correct, may be a new way to begin planetary system formation process (see also Clarke & Lodato 2009).

5.2 Metallicity correlation

Observations show that the fraction of stars orbited by a giant planet increases strongly with metallicity of the star (Fischer & Valenti 2005). As in the CA model, more solids in the gas enable more massive solid cores to be built. We also assume that if no solid core is built, the GE is completely destroyed close to the star; all of the GE material presumably accretes on to the star.

In detail, core formation requires \( t_{\text{migr}} < t_{\text{vap}} \) (Section 2.2). Dust opacity, \( \kappa_g \), is likely to be proportional to the metallicity and the grain mass fraction, \( f_g \). In such a model, the grain growth time-scale behaves as \( t_{\text{vap}} \propto f_g^{-5/21} \) (equation 6), whereas \( t_{\text{vap}} \propto f_g \). A \( f_g \) thus gives the GE more time to build a solid core. Further, Meru & Bate (2010) find that lower dust-opacity discs fragment closer to the star, reducing migration time (cf. equation 8). Low-metallicity GEs are likely to vaporize their grains before they make a solid core, and they also migrate inward too quickly to their ultimate demise.

5.3 Challenges and open questions

‘Tidal downsizing’ is a complex hypothesis that may turn out to not work for at least the following reasons.

(1) GEs need to be isolated or slowly accreted. If they pile up mass quickly by accretion from the disc, they become too hot to support grain sedimentation (Paper I).

(2) We assumed that GEs migrate as planets do. This is probably a good approximation when the radius of the embryo \( R_{\text{emb}} \ll R_\text{G} \), but much more work is needed to confirm this.

(3) We have seen that the time-scales of the important processes (see Section 4.1) do depend strongly on dust opacity and other parameters. Real protoplanetary discs may be such that grain growth inside the GEs is precluded or the embryos are disrupted too quickly.

6 CONCLUSIONS

The tidal downsizing hypothesis combines some of the planet-building processes from both the CA and the GI models, preserving
the strengths but not the weaknesses of these theories. Open questions remain, but on the balance we feel that the hypothesis deserves a further detailed consideration by the planet-formation community. We note that, having submitted this paper and Paper I, we discovered an independent suggestion on the possibility of terrestrial core formation by tidally disrupted giant embryos by Boley et al. (2010).

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APPENDIX A: IRRADIATIVE EVAPORATION

Irradiation of the GE by the star can affect the former strongly (Cameron et al. 1982). First we estimate the radius $R_{\text{lock}}$ below which the temperature of the surface layers of the GE is set by the irradiation rather than the internal radiation. This is found by equating the stellar radiation luminosity incident on the GE, $L_{\text{irr}} = L_\star \pi R_{\text{emb}}^2/(4 \pi R_{\text{lock}}^2)$, to the isolated GE radiative luminosity, $L_\text{ev}(t)$. Since $L_{\text{ev}}(t) \propto T(t)^{-4} \propto (1 + 2t/\tau_0)^{-1/2}$ for the GE (Paper I), the result for $R_{\text{lock}}$ at $t = \tau_0$ and $L_\star = L_{\odot}$ is

$$R_{\text{lock}} \approx 12 \text{ au} \, m_1^{-1} R_{\odot}^{1/4} \alpha_{\text{ev}}^{1/4} \sigma T_{\text{ev}}^{1/2} \left( \frac{H}{0.2 R_\star} \right)^{1/2}. \quad (A1)$$

Irradiation can also disrupt the GE when the irradiation temperature, $T_{\text{irr}} = (L_{\text{irr}}/4 \pi R_{\text{emb}}^2 \sigma)$ is comparable to the mean temperature (equation 1) inside the GE, e.g. $T_{\text{irr}} = \eta_{\text{ev}} T(t)$, with $\eta_{\text{ev}} \lesssim 1$. For one of the fixed planet location runs, Cameron et al. (1982) found $\eta_{\text{ev}} \sim 0.5$ (cf. their fig. 2). As $R_{\text{ev}} = (L_\star/4 \pi \sigma T_{\text{ev}}^4)^{1/2}/(\tau_0/2 t_0)$, we have

$$R_{\text{ev}} \approx 1 \, \text{au} \, \alpha_{\text{ev}}^{2/3} R_{\odot}^{2/3} \left( \frac{H}{0.2 R_\star} \right)^2 \left( \frac{0.5}{\eta_{\text{ev}}} \right)^2 \, m_1^{-1/3}. \quad (A2)$$

For fiducial parameters, tidal disruption of GEs occurs earlier (at larger radii) than the irradiative evaporation. Furthermore, as noted by the referee, the giant embryo may be shadowed by the disc if the disc scaleheight, $H$, is larger than the GE size, $R_{\text{emb}}$. Thus we expect tidal disruption of the GEs to be more frequent. Note however different parameter dependencies in equations (12) and (A2). In general both processes may be important in removing GE envelopes, with irradiation becoming more important for higher mass stars.

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