Hot Super Earths: disrupted young jupiters?

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ABSTRACT
Recent *Kepler* observations revealed an unexpected abundance of "hot" Earth-size to Neptune-size planets in the inner $0.02-0.2$ AU from their parent stars. We propose that these smaller planets are the remnants of massive giant planets that migrated inward quicker than they could contract. We show that such disruptions naturally occur in the framework of the Tidal Downsizing hypothesis for planet formation. We find that the characteristic planet-star separation at which such "hot disruptions" occur is $R \approx 0.03-0.2$ AU. This result is independent of the planet's embryo mass but is dependent on the accretion rate in the disc. At high accretion rates, $\dot{M} \gtrsim 10^{-6}\,\mathrm{M_\odot}\;\mathrm{yr}^{-1}$, the embryo is unable to contract quickly enough and is disrupted. At late times, when the accretion rate drops to $\dot{M} \lesssim 10^{-8}\,\mathrm{M_\odot}\;\mathrm{yr}^{-1}$, the embryos migrate sufficiently slow to not be disrupted. These "late arrivals" may explain the well known population of hot jupiters. If type I migration regime is inefficient, then our model predicts a pile-up of planets at $R \sim 0.1$ AU as the migration rate suddenly switches from the type II to type I in that region.

1 INTRODUCTION

Standard proto-planetary disc models (Chiang & Goldreich 1997) show that the inner ~ 0.1 AU region is too hot to allow existence of small solid particles there. Thus planets should not be able to grow there. Yet observations of nearby solar type stars show that many of them do host planets in that inhospitable to planet formation region. The very first exoplanet to be convincingly detected had the separation of $R \sim 0.05$ AU to its parent star and had a mass of about that of Jupiter (Mayor & Queloz 1995). Such gas giant planets circling their parent stars in a close proximity ($R \lesssim 0.1$ AU) are now called "hot jupiters". It is believed that they are explained by the inward radial drift (migration) of the planets born further out (Lin et al. 1996).

The *Kepler* mission has recently produced a number of surprising results (Borucki et al. 2011), one of which is that there is an even greater number of smaller planets, e.g., Earth-size to Neptune-size, in that region. It is similarly obvious that these smaller "hot" planets also had to be brought there from further out by an inward radial migration. One practical difficulty in testing this idea, though, is that the migration of smaller planets is expected to occur in the poorly understood "type I" regime (Paardekooper & Papaloizou 2008). This is different from the better understood "type II" regime by which the giant planets migrate (Lin & Papaloizou 1986). This theoretical difficulty leads to a large range in uncertainties in the predictions of the detailed Core Accretion model calculations (e.g., see Fig. 5 in Ida & Lin 2008).

Recently, the key importance of the radial migration of the earliest gas condensations formed in the massive proto-planetary discs by the gravitational instability was realised (Vorobyov & Basu 2006; Boley et al. 2010). Analytical estimates (Nayakshin 2010a) and numerical simulations (Vorobyov & Basu 2006, 2010; Boley et al. 2010; Cha & Nayakshin 2010) show that these condensations can migrate all the way from their birth-place in the outer $R \sim 100$ AU disc into the inner $\sim$ few AU disc and be disrupted there during the earliest massive disc phase ($t \lesssim$ few$\times 10^5$ yrs, typically).

It was pointed out by Boley et al. (2010) and Nayakshin (2010a) that this migration-and-disruption sequence yields an unexplored way of forming terrestrial like planets. If dust grows and sediments in the centre of the clump and forms a solid density core there, then tidal disruption of the gas clump may leave a solid core – an Earth-like proto-planets (note the connection to earlier ideas of McCrea & Williams 1965; Boss 1998; Boss et al. 2002). Nayakshin (2010c,b) used a simple spherically symmetric radiation hydrodynamic code with the dust grains as a second fluid to delineate the conditions when such a mechanism for the solid core growth can work. Based on the potential promise of these ideas, Nayakshin (2010a) formulated the "Tidal Downsizing" (TD hereafter; Nayakshin 2010a) hypothesis for planet formation. In this picture a partial disruption of a $\sim 10 M_J$ gas clump (which we also call giant embryos; GEs) leaves a giant planet, whereas a complete disruption yields a terrestrial like planet.

In this Letter we continue to assess the potential utility of the TD hypothesis to planet formation. We note that another ingredient, muted but not explicitly considered by Boley et al. (2010); Nayakshin (2010c,b,a), must be included in the scheme. To explain it, consider isolated GEs first. As they contract, their internal temperature increases. At early

times the rate of this contraction is controlled by the radiative cooling rate of the embryo – which is by the rate at which the embryo can get rid of the excess energy. However, when temperature $T_{2nd} \approx 2000$ K is reached, molecular hydrogen disassociates. This process is an efficient energy sink, which allows the embryo to contract rapidly – in fact collapse hydrodynamically – without the need to radiate the energy away. The embryo collapse stops only at much higher densities, and temperatures as high as 10^4 K, at which point hydrogen is ionised. The embryo must then continue a slower contraction, again regulated by the rate at which its energy is radiated away. The collapse is known as the "second collapse" in the star formation literature (Larson 1969), when the "first cores" of masses $\sim 50 M_J$ collapse (Masunaga & Inutsuka 2000) to become "second cores", which are the proper proto-stars.

In the TD hypothesis for planet formation, the second collapse may be the last step to making a gas giant planet. However, as we show below, this final step is not automatically successful – planets continuing to migrate rapidly towards their parent stars may still be disrupted at $R \sim 0.1$ AU. We suggest this process as a way of forming the hot Super Earths observed by the *Kepler* mission (Borucki et al. 2011).

2   THE SECOND EMBRYO

In analogy to the star formation literature, we refer to the GEs that are mainly molecular, embryo's temperature $T_e < T_{2nd}$, as the "first GEs"; those where H_2 is disassociated are termed "second GEs" instead.

2.1   Contraction and collapse of the first embryo

To illustrate the main point of this paper, we calculate the contraction of a giant embryo with "typical" parameter values (e.g., those that appear quite reasonable to us for a solar metalicity disc around a $\sim$ solar mass star; see Nayakshin 2010a). In particular, the embryo mass is $M_e = 10 M_J$, the normalised dust opacity is $k_* = 0.5$, and the grain mass fraction $f_g = 0.01$. The embryo is initialised as a first core of same mass (see Nayakshin 2010c).

Figure 1 shows the time evolution of the embryo's central temperature (solid, in units of 10^3 K), the gas density (dotted, in units of 10^{-8} g cm^{-3}), and the outer radius of the embryo, r_e, (dashed, in units of 1 AU). The calculation is carried out with an updated version of the 1D gas-dust grains radiative hydrodynamics code of Nayakshin (2010c,b). Instead of using an ideal gas equation of state with $\gamma = 5/3$, the code now uses the equation of state appropriate for molecular hydrogen, including disassociation and rotational and vibrational degrees of freedom for H_2, with the orto-hydrogen to para-hydrogen ratio fixed at 3:1 (cf. Boley et al. 2006).

Despite the updated equation of state, the evolution of the first embryo is quite similar to that of the cases studied in Nayakshin (2010b). This may not be entirely surprising given the similar insensitivity of the first (gas) cores to the equation of state as found by Masunaga et al. (1998); Masunaga & Inutsuka (2000). The embryo contracts and heats up, whereas dust grains grow. By time $t \sim 1000$
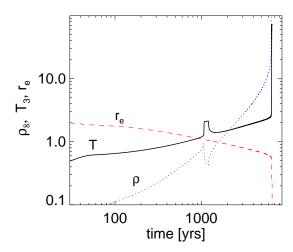

Figure 1. The embryo's temperature (in units of 10^3 K), density (in 10^{-8} g cm^{-3}) and radial size, r_e, in AU, as a function of time, as labelled on the figure. Note the abrupt change near the end of the calculation, marking the second collapse, when the central temperature reaches $T \sim 2300$ K. The bump in the central temperature near $t = 1000$ yrs is caused by the formation of a $\approx 5 \, M_\oplus$ solid core inside the embryo.

yrs, the grains increase in size to about 20 cm. Their density exceeds that of the gas in the centre of the embryo; they become self-gravitating and form a solid core of mass $M_c \sim 5 \, M_\oplus$. In Figure 1, the solid core formation is notable by the bump in the central temperature. After the core formation, the central region becomes hotter than grain vaporisation temperature of ≈ 1400 K, evaporating the grains, and thus terminating further core growth (see Nayakshin 2010b, for details on this negative feedback loop). The central region also expands slightly. Most of the GE is however unaffected by the solid core in this case, and the curves resume their otherwise monotonic behaviour a few hundred years later.

At $t \approx 6.5 \times 10^3$ yrs, the GE goes through the second collapse when the central temperature exceeds about 2300 K. The embryo radius drops rapidly, while the density and the temperature increase strongly. The first embryo becomes the second in our terminology.

2.2   The contraction of the second embryo

Our radiation hydrodynamics code is not well suited (Nayakshin 2010b) to follow the long cooling and contraction of the second embryo. However, there is a body of work on the hydrostatic contraction of very low-mass stars and Jupiter-mass planets (e.g., Grossman & Graboske 1973; Graboske et al. 1975), which allows us to describe the process with a good degree of confidence. Let t_2 be the time of the second collapse of the embryo. As is well known, the embryo spends the initial contraction stages on the Hayashi track. During this phase, the outward energy transfer is dominated by convection. The effective temperature, T_{eff} is almost constant at $\log T_{eff} \sim 3.1 - 3.3$ [see Figs 1 in Grossman & Graboske (1973); Graboske et al. (1975)]. The luminosity of the embryo is then $4\pi r_e^2 \sigma T_{eff}^4$.

With this simple cooling model, we solve for the evolution of the second GE radius, $r_e(t)$,

$$\frac{dE_{\mathrm{GE}}}{dt} = 4\pi r_e^2 \sigma_B T_{\mathrm{eff}}^4 \ , \qquad (1)$$

where the energy of the GE is defined with the positive sign as $E_{\mathrm{GE}} \approx GM_e^2/2r_e$. A trivial integration yields[1],

$$r_e^3(t) = \frac{r_2^3}{1 + Ar_2^3(t - t_2)} \ . \qquad (2)$$

Here r_2 is the GE radius at the time of the second collapse, t_2, and $A = 24\pi\sigma_B T_{\mathrm{eff}}^4/(GM_e^2)$. This model does not take into account the electron degeneracy pressure in the GE, but that becomes important only after $t \gtrsim 10^6$ yrs, and would make disruption of the planets even more likely.

Evaluation of equation (2) shows that at times $(t - t_2) \gtrsim 100$ yrs, the initial radius of the embryo is quickly forgotten, and the contraction proceeds as

$$r_e(t) = \left(\frac{1}{A(t - t_2)}\right)^{1/3} \ . \qquad (3)$$

The second embryo's density as a function of time is

$$\rho_e(t) = \frac{3M_e A(t - t_2)}{4\pi} = \frac{18\sigma T_{\mathrm{eff}}^4}{GM_e}(t - t_2) \ . \qquad (4)$$

In terms of absolute values, the initial density of the second embryo is at least 10^{-6} g cm^{-3} (cf. Fig. 1) and rises with time according to

$$\rho_e(t) = 6 \times 10^{-4} \ \mathrm{g \ cm}^{-3} \ \frac{(t - t_2)}{10^4 \ \mathrm{yr}} \frac{10M_J}{M_e} \ , \qquad (5)$$

where we set $\log T_{\mathrm{eff}} = 3.1$ for certainty.

2.3 Vulnerability of young massive planets

A distance R away from the star, the tidal density is

$$\rho_{\mathrm{t}} = \frac{M_*}{2\pi R^3} \approx 10^{-7} \ \mathrm{g \ cm}^{-3} \ \frac{M_*}{\mathrm{M}_\odot} R_{AU}^{-3} \ , \qquad (6)$$

where M_* is the stellar mass, and $R_{AU} = R/1$ AU. A giant embryo that migrated to a distance R is disrupted if the embryo's density $\rho_e \lesssim \rho_{\mathrm{t}}$. The first and the second embryos have considerably different internal densities. The "first embryos" are characteristically disrupted at $R \gtrsim 2$ AU (Nayakshin 2010a). We term these disruptions "cold" and do not consider any further here.

To evaluate the second GE's fate, we need to estimate its migration rate. We assume that there is only one such GE in the inner $R \lesssim$ few AU at any one time. Due to its significant mass, the GE migrates in the type II regime. As shown by Ivanov et al. (1999), the migration time, t_{mig}, is shorter than but is comparable to the "accretion time", $t_{\mathrm{a}} = M_e/\dot{M}$, where $\dot{M}$ is the accretion rate in the disc. In the TD model, the planets are born in the very early gas-rich phase of the disc when the proto-star is far from its final mass. The accretion rate during that phase is $\dot{M} \sim M_*/t_{\mathrm{ff}}$, where $t_{\mathrm{ff}} \sim 10^5$ yrs is the free-fall time for typical interstellar molecular gas cores of $\sim 1 \, \mathrm{M}_\odot$ mass (Larson 1969). Thus,

$$t_{\mathrm{mig}} \lesssim \frac{M_e}{\dot{M}} = 10^3 \ \mathrm{yrs} \ \frac{M_e}{10M_J} \frac{10^{-5} \, \mathrm{M}_\odot \mathrm{yr}^{-1}}{\dot{M}} \ . \qquad (7)$$

Now, this time scale is to be compared with the Kelvin-Helmholtz time scale for isolated giant planets, which is of the order of $t_{\mathrm{KH}} \sim (10^4 - 10^5)$ yrs (e.g., see Figs. 2 & 3 of Graboske et al. 1975). In fact, any additional effects we can think off, e.g., stellar irradiation (e.g., Cameron et al. 1982), tidal heating, energy stored in the rotation of the GEs, accretion of planetesimals, etc., should only increase t_{KH}.

We can now estimate the embryo-star separation at which the disruption occurs, R_{hot}, e.g., where $\rho_e = \rho(R_{\mathrm{hot}}$. For this we note that $(t - t_2)$ in equation (4) should be of the order of t_{mig}. Indeed, this is the time it takes the embryo to migrate inwards, and thus the embryo's age should be comparable to that. Entering t_{mig} instead of $(t - t_2)$ in equation (4), we find that the dependence on the embryo's mass cancels out, and we arrive at

$$R_{\mathrm{hot}} = \left[\frac{GM_*\dot{M}}{36\pi\sigma T_{\mathrm{eff}}^4}\right]^{1/3} = 0.12 \ \mathrm{AU} \left(\frac{\dot{M}}{10^{-5} \, \mathrm{M}_\odot \mathrm{yr}^{-1}}\right)^{1/3} \ , \quad (8)$$

where we set $\log T_{\mathrm{eff}} = 3.1$ and retained the dependence on $\dot{M}$ only. We term this inner disruption "hot" to distinguish from the more distant cold disruptions. Equation 8 shows that a second GE entering the inner ~ 0.1 AU in an early disc phase, when $\dot{M}$ is very high, is likely to be tidally disrupted. On the other hand, "late arrivals", when $\dot{M} \lesssim 10^{-8} \, \mathrm{M}_\odot$ yr^{-1}, may survive and contract into hot jupiters as the disc runs out of mass, presumably due to photo-evaporation (Alexander et al. 2006).

3 AN ILLUSTRATIVE MODEL

We now present two approximate example calculations that are complete in the sense that they start off with the embryo's birth at $R = 100$ AU and they end with the embryo arriving in the innermost disc. We use the model embryo calculated in §2.1 and 2.2, and an approximate radial migration model of Nayakshin (2010a). We consider two opposite limiting cases to illustrate the points made in 2.3.

3.1 A disrupted hot jupiter

In the first case, presented in Figure 2, the accretion disc is massive and the accretion rate is high. In particular, the initial mass of the star is $M_* = 0.5 \, \mathrm{M}_\odot$, the doubling timescale for the star, $t_{\mathrm{db}} = 10^5$ yrs. This yields an accretion rate through the disc of $5 \times 10^{-6} \, \mathrm{M}_\odot$ yr^{-1}. At $t = t_{\mathrm{db}}$, the assembly of the star is assumed complete (its mass reaches 1 $\mathrm{M}_\odot$), and the disc torques are abruptly removed.

For simplicity we assume that the mass of the GE is constant until it is disrupted dynamically. 3D simulations of embryos migrating in gas discs show destruction of the embryos in a matter of two or three orbits (Boley et al. 2010; Cha & Nayakshin 2010) once they fill their Roche lobes.

The upper panel of Figure 2 shows the radial location of the embryo. The embryo migrates into the inner ~ 0.1 AU region of the disc in less than 10^5 yrs due to the high disc accretion rate. The middle panel shows the evolution of

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[1] A similar model can be used to describe the contraction of young $M_* \sim \mathrm{M}_\odot$ proto-stars as well (e.g., Cameron 1995).

the Hills radius, r_H, and the embryo's radius, r_e. r_e is initially one to two orders of magnitude smaller than the Hills radius, especially right after the second collapse. The lower panel shows the embryo's temperature evolution, which is comprised of two parts: the first one calculated as in §2.1 (and shown in Figure 1) until the second collapse occurs, at which point we switch to the model of §2.2, with T found through the virial relation of the embryo.

The "hot" disruption of the embryo occurs at time $t \approx 6 \times 10^4$ yrs, at the embryo-star separation of $R = 0.06$ AU. Note that disruption of the gaseous envelope leaves a solid core behind since the solid core formation occured much earlier. The solid core migrates slightly to $R \sim 0.045$ AU by $t = t_{db}$. This last bit of radial migration is via type I and may in reality be far less efficient (Paardekooper & Papaloizou 2008; Ida & Lin 2008).

3.2   A tidally stable hot jupiter

In the other example we take a proto-star that is closer to its final mass, $M_* = 0.8\,M_\odot$, accreting at a rate of $10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$ for 2×10^6 yrs. Figure 3 shows that in this case the embryo migrates much slower. By the time it arrives in the innermost disc, the embryo radius, r_e, dropped to about 2×10^{-3} AU. The embryo is too compact to be disrupted unless it migrates even further to ~ 0.01 AU (it is likely to stall before that due to the magnetospheric cavity in the inner disc).

4   DISCUSSION

We suggested here that massive gaseous proto-planets in the "second" configuration, migrating rapidly inward, are tidally disrupted in the inner ~ 0.1 AU. If these protoplanets contain solid cores, then the cores remain unaffected by the disruption as their densities are much higher. For solid cores more massive than $\sim 20\,M_\oplus$, parts of the gaseous envelopes may be retained as well (Nayakshin 2010b). Therefore, the hot disruption of gas giant planets could in principle result in the production of purely solid and also solid plus gas envelope planets similar to those found in the *Kepler* data. Further modelling of the regions closest to the solid cores inside the embryos is needed for a more quantitative statement.

The outcome of a hot jupiter arriving in the inner 0.1 AU strongly depends on the migration rate of the latter and its age. If the proto-planet is "old", e.g., $\gtrsim 1$ Myrs, then it is too dense to be disrupted near the star. The observed hot jupiters in our interpretation are the planets that arrived in the inner 0.1 AU somewhat late, when they were already compact, and when the disc was running out of material.

Some of the *Kepler* Neptune and Earth-size planets could have parted with their gaseous envelopes in the cold disruptions at a few AU, and then migrated inward in the disc. This would make for a second channel of making these planets in the inner disc. However, the location of hot disruption is quite well defined, $R \sim 0.03 - 0.2$, due to the strong dependence of the tidal density on R. Therefore we predict a pile-up of smaller planets at those radii *as long as* the actual type I migration rate of the disruption remnants is far smaller than the theoretical type I migration rate (cf.
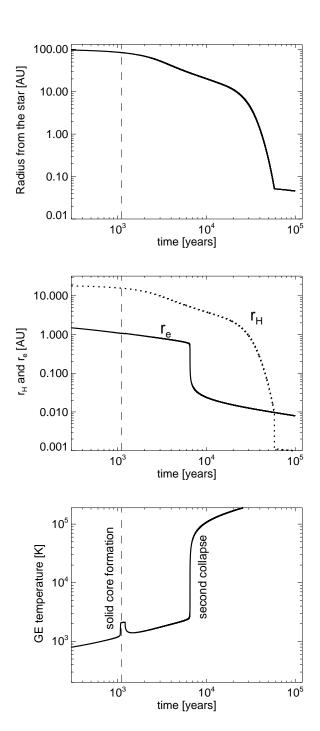

Figure 2. Formation of a "hot Super Earth" starting from a giant embryo of 10 Jupiter masses. **Upper panel**: Radial position of the embryo versus time. The GE starts off at $R = 100$ AU. The vertical dashed line marks the time when a solid core forms inside the embryo. **Middle**: Radius of the embryo, r_e, and the Hills radius, r_H. The GE gaseous envelope is assumed to be completely disrupted when the two sets of curves meet. **Lower**: Temperature of the first cores as a function of time. Note the strong jump at the second collapse.
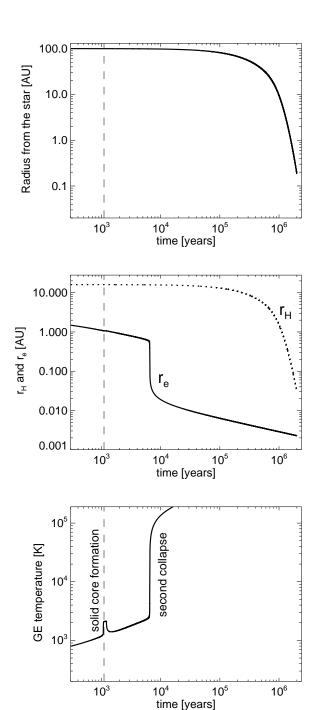
Figure 3. Same as Figure 2 but for the disc accretion rate of $10^{-7}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. The embryo is not disrupted in the inner disc since it has had enough time to contract to much higher densities.

Ida & Lin 2008). Such a pile-up may be testable with the current exoplanet data.

5   ACKNOWLEDGMENTS

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