

Positive metallicity correlation for coreless giant planets

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ABSTRACT

Frequency of detected giant planets is observed to increase rapidly with metallicity of the host star. This is usually interpreted as evidence in support of the Core Accretion (CA) theory, which assembles giant planets as a result of formation of a massive solid core. A strong positive planet-metallicity correlation for giant planets formed in the framework of Gravitational disc Instability (GI) model is found here. The key novelty of this work is “pebble accretion” onto GI fragments which has been recently demonstrated to accelerate contraction of GI fragments. Driven closer to the star by the inward migration, only the fragments that accrete metals rapidly enough collapse and survive the otherwise imminent tidal disruption. The survival fraction of simulated planets correlates strongly with the metallicity of the host star, as observed.

1 INTRODUCTION

In its original form, GI hypothesis posited that gas giants are made in situ by gravitational fragmentation of a massive protoplanetary disc (Kuiper 1951; Boss 1997). This has been correctly criticised (Rafikov 2005) since the discs can actually fragment only beyond \sim tens of AU (Rice et al. 2005). However, since simulations show that GI fragments migrate in rapidly (Vorobyov & Basu 2006; Baruteau et al. 2011), it appears perfectly feasible for them to form at \sim 100 AU but then end up arbitrarily close to the parent star due to disc migration. Furthermore, some of the fragments could give birth to Earth-mass or more massive cores due to grain sedimentation (e.g., Boss 1997; Helled & Schubert 2008; Nayakshin 2011). If these gas fragments are tidally disrupted, only the cores survive (Boley et al. 2010), which potentially provides a new pathway to forming all kinds of planets at all separations in a single framework that was called “Tidal Downsizing” (TD; Nayakshin 2010).

However, there appears to be a major inconsistency of TD/GI with observations. Giant planets are much more frequent around metal-rich hosts (Fischer & Valenti 2005). Radiative contraction of GI planets is slower at high metallicities (Helled & Bodenheimer 2011), hence predicting fewer planets surviving tidal disruption. Core Accretion (CA; e.g., Pollack et al. 1996) paradigm is, in contrast, consistent with the metallicity trend and explains it as a consequence of a more robust massive core assembly at high metallicities.

Nayakshin (2014b) showed that accretion of medium sized grains (“pebbles”, Johansen & Lacerda 2010) onto pre-collapse gas fragments actually speeds up their contraction and collapse. In this picture giant planets collapse not due to emission of radiation (like stars do) but due to accretion of metals in small grains, which acts as an effective cooling mechanism (cf. equation 2 below and figure 1). This paper presents first detailed coupled planet-disc evolutionary calculations of TD hypothesis that incorporate this new

physics, treating non-linear disc-planet interaction, the rate of grain deposition into the planet and its response to that in detail. A grid of models covering a reasonable range in poorly constrained parameters of the model (such as grain opacity, disc viscosity, etc.) is calculated to delineate statistical trends of the model. A strong positive correlation of planet survival probability with metallicity of the host is found.

2 NUMERICAL METHODS

In the protoplanetary disc environment, both gas and grains are gravitationally attracted to massive bodies embedded in it, but gas has pressure gradient forces able to resist the pull, whereas grains do not. Grains that are moderately weakly coupled to gas via aerodynamical friction – grains of a few cm in size, a_{peb} , in the inner disc, but 1 mm or less in the outer disc – are captured by the body most efficiently (Johansen & Lacerda 2010; Ormel & Klahr 2010). Pebble accretion rate appropriate for the massive planets that we study here is $\dot{M}_z = 2R_H^2 v_K \Sigma_p / a$ (e.g., Lambrechts & Johansen 2012), where v_K is Keplerian velocity at the planet’s location, a ; $\Sigma_p = f_p z_d \Sigma_d$ and Σ_d are the surface densities of pebbles and gas, respectively, and $0 \leq f_p < 1$ is the fraction of pebbles in the total grain surface density ($z_d \Sigma_d$). We assume that f_p increases linearly with z_d due to a more rapid grain growth at higher z_d , so $f_p = f_{p0}(z_d/z_\odot)$, where $f_{p0} = \text{const} \ll 1$ is a free parameter, and z_d and $z_\odot = 0.015$ is the disc and solar metallicities, respectively.

The disc surface density at the planet’s location, Σ_d , is not independent of the planet, as the planet interacts with the disc strongly. Following Nayakshin & Lodato (2012), the protoplanetary disc is described by a viscous azimuthally symmetric time-dependent model that includes the tidal torque of the planet on the disc

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R} \frac{\partial}{\partial R} \left[R^{1/2} \frac{\partial}{\partial R} (R^{1/2} \nu \Sigma) \right] - \frac{1}{R} \frac{\partial}{\partial R} (2\Omega R^2 \lambda \Sigma) \quad (1)$$

where Σ is the disc surface density at radius R , λ is the tidal torque from the planet. The torque can be either in type I (no gap) or type II (a gap in the disc is opened). Two-dimensional hydro simulations (Crida et al. 2006) show that a deep gap in the disc is opened when parameter $\mathcal{P} = 3H/4R_H + 50\alpha_{ss}(H/a)^2(M_*/M_p) \lesssim 1$, where H is the disc vertical scale height at a , and $\alpha_{ss} \ll 1$ is the disc viscosity parameter. Based on this result, we smoothly join the type I and type II regimes using the self-consistently found value of \mathcal{P} at the location around the planet. This approach is necessary since migration rates of planets depend sensitively on whether a gap in the disc is opened or not (Galvagni & Mayer 2014).

Nayakshin (2014b), Nayakshin (2014), uses a 1D spherically symmetric radiative hydrodynamics (RHD) code with grains treated as a second fluid to simulate contraction of an otherwise isolated planet that accretes grains. Such an approach is unfortunately too computationally expensive in the framework of a full disc-planet interaction problem, and forced previous workers to use analytical models for the planets (e.g., Nayakshin 2010; Forgan & Rice 2013).

Here, a simpler “follow the adiabat” approach (Marleau & Cumming 2014; Fortney & Hubbard 2004) in which the planet is assumed isentropic, is used. This is a reasonable approximation since the energy transfer inside the planet is strongly dominated by convection even at Solar opacities/metallicities (Helled & Bodenheimer 2011). For a given initial conditions, e.g., the planet mass, M_p , the central fragment’s temperature, T_c , and grain properties for each radial zone in the planet, a solution of the equilibrium equations is found by iterations on the central gas density. This determines planetary radius, R_p , and the total energy of the planet, E_{tot} , which is then evolved in time according to

$$\frac{dE_{\text{tot}}}{dt} = -L_{\text{rad}} - \frac{GM_p \dot{M}_z}{R_p}, \quad (2)$$

where L_{rad} is the radiative luminosity of the planet, and the last term on the right is the change in the gravitational potential energy of the planet due to grain accretion on it at the rate \dot{M}_z . After evolving E_{tot} by a small amount, a grain growth step of same duration then follows. The new total energy and grain properties in every zone in the planet then allow us to determine the new planet’s structure, which is found by iterating on both T_c and the central gas density. The procedure is then repeated. We tested the isentropic approach against the RHD code for a number of fragment contraction cases, including metal loading tests on the planet, and found an acceptable (typically $\sim 10 - 20\%$) agreement.

It is important to point out the following. Pebbles sedimenting down onto the planet do so at differential velocities (usually linearly proportional to their size, a_{peb}). From experiments it is well known that grains colliding at velocities exceeding a few m s^{-1} fragment (e.g., Blum & Wurm 2008). In the context of TD, Nayakshin (2014) showed that grain-grain collisions limits the grain size inside the planets to a few cm. Therefore, the velocity with which pebbles impact the planet, v_{imp} , cannot be much larger than a few m s^{-1} , which is very small compared to the escape velocity from the planet, $\sqrt{2GM_p/R_p} \approx 1500 \text{ m s}^{-1}$, where $M_p = 1 \text{ M}_J$ and $R_p = 1 \text{ AU}$ is used. For this reason the kinetic energy

input term in equation 2, $\dot{M}_z v_{\text{imp}}^2/2$, is neglected. This is in stark contrast to CA theory (CA; e.g., Pollack et al. 1996) where the solids from the disc enter the planet as planetesimals – huge rocks very poorly coupled to gas – and impact the growing planets at $v_{\text{imp}} \gtrsim 2GM_p/R_p$ and therefore heat the gaseous envelope strongly. Solids may nevertheless heat the gas envelope in both scenarios if they eventually reach a massive solid core in the planet. This effect is not considered here but is included in a follow-up paper.

Following Helled & Bodenheimer (2011), dust opacity in the fragment is directly proportional to the metallicity of the gas, z : $\kappa(\rho, T) = f_{\text{op}} \kappa_0(\rho, T)(z/z_{\odot})$ where $\kappa_0(\rho, T)$ are the interstellar gas plus dust opacities from Zhu et al. (2009) which assume Solar metallicity, z_{\odot} , and $f_{\text{op}} = \text{const} \leq 1$ is a positive constant which may be smaller than unity due to grain growth.

3 PLANET SURVIVAL EXPERIMENTS

Before presenting the more complex planet-disc calculations, Figure 1 shows evolution of central temperature for four isolated GI fragments of mass $M_p = 1 \text{ M}_J$. Black curves are for two different constant fragment metallicities, $Z = 1$ and 5, where $Z = z/z_{\odot}$. The red curves are for fragments with metal abundance increasing at rate

$$\dot{M}_z = \frac{z_{\odot} M_p}{t_z}, \quad (3)$$

with t_z labelled on the figure. The inset shows metallicity z for the four cases. The red and the $Z = 1$ black curves end when T_c reaches $\sim 2000 \text{ K}$, at which point H_2 molecules dissociate, and the fragment collapses dynamically to much higher densities. This marks formation of a dense young Jupiter that could survive tides in the inner disc. The $Z = 5$ fragment contracts the slowest due to a high dust opacity. In contrast, $\dot{M}_z > 0$ fragments (red curves) contract faster than the $Z = 1$ one. The metallicity of the fragment corresponding to the dot-dashed curve is $Z = 20$ yet it collapses ~ 5 times faster than the $Z = 1$ case. Such a collapse could be termed “dark” as relatively little radiation is emitted during contraction of the planet.

As explained in Nayakshin (2014b) in detail, and can also be qualitatively seen from equation 2, accretion of pebbles by the fragments is a form of non-luminous cooling which is directly proportional to \dot{M}_z . This must help fragments to survive. For example, if the fragments from figure 1 were migrating inward on a time scale of 10^4 years, the $Z = 5$ one would have been tidally destroyed in about 20,000 years, whereas the $t_z = 250$ years fragment would have collapsed and could therefore continue to migrate almost arbitrarily close to the star.

To quantify these ideas, Figure 2 tests survival of fragments born at $a_0 = 120 \text{ AU}$ for the pebble accretion model at three disc metallicities, $Z_d \equiv (z_d/z_{\odot}) = 0.5, 1$ and 2 for the dashed, dotted and solid curves, respectively. Colours are used to delineate different quantities for the same fragment. The top panel shows time evolution of the planet’s separation, a , planet’s radius, R_p , and Hill radius, $R_H = a(M_p/3M_*)^{1/3}$. Panel (b) shows metallicity of the planets, (c) shows central temperature, T_c , and (d) compares the migration time scale, $t_{\text{migr}} = -a/(da/dt)$, where a is planet’s

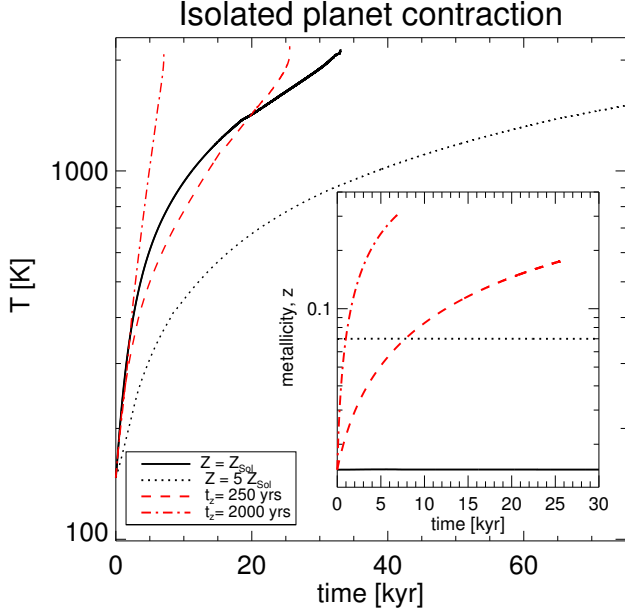


Figure 1. Radiative contraction of four GI fragments of mass $M_p = 1 M_J$. Black curves show $z = \text{const}$ planets, while red curves show two pebble accretion cases. The faster the metals are added to the planet, the faster it collapses to higher densities, increasing the chances of its survival.

semi-major axis, with the metal loading time scale, t_z , calculated self-consistently. Namely, first M_z in the Hill’s regime (see Lambrechts & Johansen 2012) is found from the simulation, and then equation 3 is inverted to find t_z .

Initially, $R_p \ll R_H$, so that tidal forces from the star are weak compared to the planet’s self-gravity. As the planet migrates closer in, R_p and R_H decrease at different rates, and the planet is tidally disrupted if $R_p \geq R_H$.

In all three cases, radiative cooling of the planet is negligible, that is, L_{rad} is much smaller (or even *negative* due to planet irradiation from the disc, see Vazan & Helled 2012) than the last term in equation 2. The planets therefore contract mainly due to accretion of pebbles. The higher the disc metallicity, the quicker the planet’s metallicity increases with time, and the faster it contracts (note that R_p decreases and T_c increases). The lowest metallicity planet is disrupted the soonest, at $a = 3.3$ AU. $Z_d = 1$ planet is about twice as compact, so it makes it to $a = 1.7$ AU before being disrupted. This planet almost manages to collapse (reaches $T_c \approx 1500$ K), but \dot{M}_z plummets when a deep gap around the planet is opened after $t \approx 55,000$ years (note that $t_z \rightarrow \infty$ at later times). Starved of metals, the planet stops contracting and gets disrupted soon thereafter. In contrast, the $Z_d = 2$ planet contracts much more rapidly, and collapses at $t \approx 33,000$ years, before it is tidally compromised. This planet could be driven into the “hot Jupiter” region by a continuing disc migration, not simulated here.

4 A GRID OF MODELS

These results suggest that GI planets may be more likely to survive at higher Z_d . To ascertain metallicity trends of the model, given large uncertainties in the input physics, a grid of fragment survival experiments just like those described in figure 2, but now repeated for parameters varied over a reasonably broad range, is run. Parameter values in the grid are: disc viscosity $\alpha_{\text{SS}} = 0.01, 0.02, 0.04$; planet’s birth location, $a_0 = 70, 120$; pebble mass fraction $f_{p0} = 0.05, 0.1$ and 0.2 . We also tested type I migration torque at $0.5, 1$ and 2 times that from Bate et al. (2003). The grid of models is calculated for 9 different disc metallicity values between $Z_d = 1/3$ and $Z_d = 3$, and the fraction of planets surviving (that is collapsing before being tidally disrupted) is then found for each metallicity bin. This comprises 486 planet survival experiments in total.

Figure 3 shows the results for $M_p = 1 M_J$. Fragments are indeed much more likely to survive at high z_d than they are at low z_d . Black solid line shows the full grid of models, while the blue dotted and the red dashed lines show $f_{p0} = 0.05$ and 0.2 only, respectively. The correlation with metallicity remains strong but is shifted to higher z_d (lower z_d) if pebbles are less (more) abundant. The strength of the correlation appears sufficient to explain qualitatively the observed trend of giant planet frequency being proportional to Z^2 (Fischer & Valenti 2005). Figure 4 shows the same grid of survival experiments as shown in fig. 3, but now conducted for different planet’s masses. It is seen that the correlation is qualitatively unchanged for $M_p = 0.5 M_J$ and $M_p = 2 M_J$ planets (which are abundant in the Fischer & Valenti 2005, sample).

The final mass of the planet may be different from the pre-collapse value for two reasons. Firstly, due to a substantial angular momentum of pre-collapse clumps (e.g., Boley et al. 2010; Galvagni et al. 2012), not all of the planet’s mass may end up in the planet, some may end up in the circum-planetary disc and then be lost. On the other hand, more gas could in principle be accreted from the disc onto the planet. These effects may extend the positive metallicity correlation found here for the $0.5 - 2 M_J$ planets to both lower and higher masses.

5 DISCUSSION AND CONCLUSIONS

Planet survival experiments in the context of Tidal Downsizing model for planet formation (Nayakshin 2010) were performed. The new ingredient in the model is “pebble accretion” of grains from the disc onto the fragments, plus simultaneous treatment of the coupled planet and disc evolutionary equations. Since pebble accretion accelerates collapse of gas fragments, a strong positive correlation of the fraction of survived giant planets versus metallicity of the host is found. TD/GI origin for giant gas planets is not, therefore, in conflict with the observed planet-metallicity correlation. Formation of solid cores within the planets is turned off in the present paper for simplicity but is to be considered and reported on in a forthcoming paper.

Galvagni & Mayer (2014) find results that are somewhat in disagreement with ours. They find a much more copious production of giant planets with-

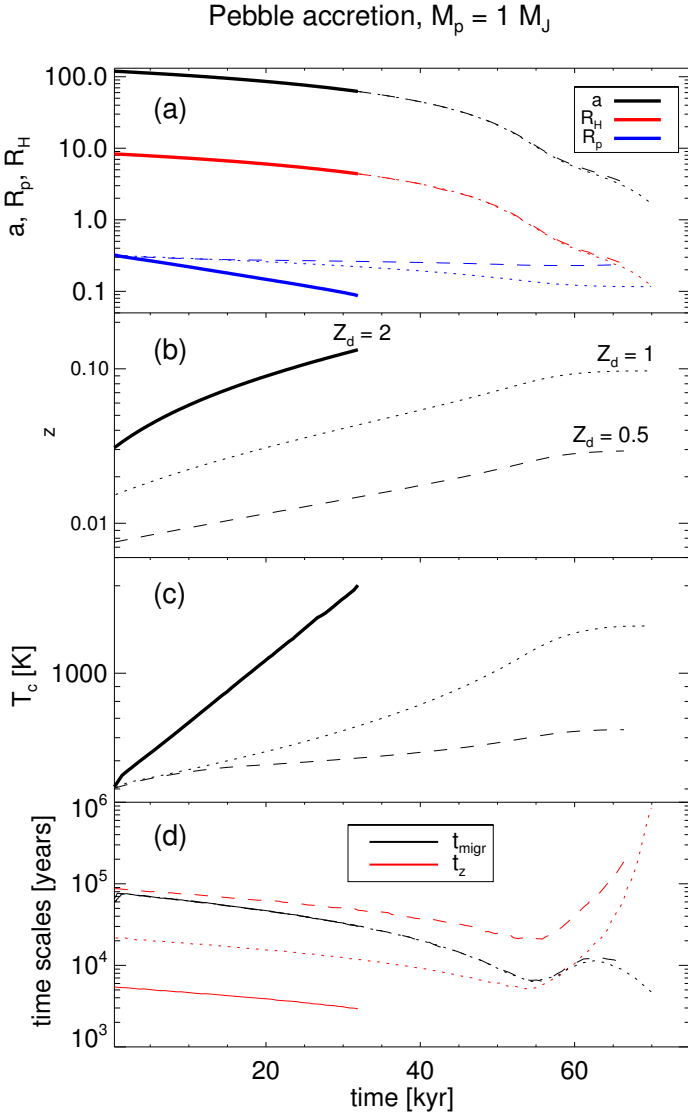


Figure 2. Evolution of a gas fragment accreting grains from the disc at three different disc metallicities ($Z_d = 2, 1$ and 0.5 , for solid, dotted and dashed curves, respectively). Panels show: (a) planet-star separation, a , Hill's and planet's radii; (b) planet's metallicity, z ; (c) central temperature of the planet; (d) migration and grain loading time scales. For all three cases, the fragment mass is $1 M_J$, birth location $a = 120$ AU, disc mass $100 M_J$ within 150 AU, viscosity parameter $\alpha_{SS} = 0.02$, pebble fraction $f_{p0} = 0.1$, and planet opacity parameter $f_{op} = 0.3$. $Z_d = 2$ fragment contracts rapidly, reaching 2000 K and collapsing at $t \approx 32,000$ years. The metallicity of the planet is about $10z_\odot$ at the point of collapse. The $Z_d = 1$ and 0.5 fragments contract less rapidly due to lower metal supply (resulting in longer t_z , see panel d), and are tidally disrupted at $a = 1.7$ and 3.3 AU, respectively. The $Z_d = 1$ planet would have actually collapsed if not for a deep gap in the disc, opened at $t \approx 55,000$ years, which cuts off grain accretion to almost zero.

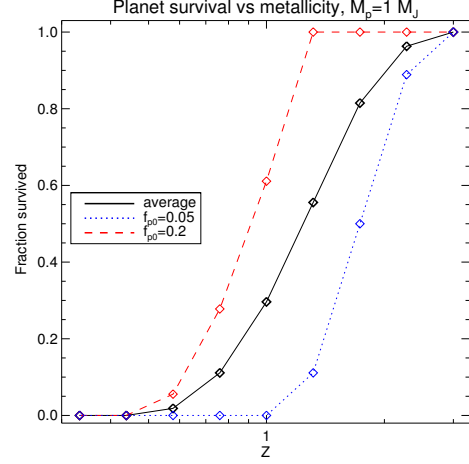


Figure 3. Planet survival probability versus Z , the metallicity in Solar units, for a planet of $M_p = 1 M_J$ mass and disc parameters covering a range of properties. The black diamonds show the full grid of models, while the blue and the red symbols show results for $f_{p0} = 0.05$ and $f_{p0} = 0.2$ (low and high pebble content, respectively). There is a strong positive planet survival correlation with the metallicity of the host disc.

out pebble accretion which we found to be instrumental in driving the planets to collapse here. This difference in the results may be in part due to a different radiative cooling formalism used by Galvagni & Mayer (2014). Namely, these authors use earlier results of Galvagni et al. (2012) who studied disc fragmentation and gas fragment collapse in 3D simulations, which is clearly preferable to our 1D study in that aspect. On the other hand, in Galvagni et al. (2012) the radiative cooling of the fragments is modelled with a semi-analytical prescription (as commonly done in 3D simulations of discs by a number of authors, see, e.g. Boley et al. 2010; Cha & Nayakshin 2011) rather than with a radiative transfer scheme. Our results, on the other hand, are motivated (Nayakshin 2014b) by radiative hydrodynamics simulations of contracting planets in which transfer of radiation is calculated with the classical radiation diffusion approximation, albeit in 1D. Ideally, one would like to combine 3D hydrodynamics with 3D radiative transfer to study formation of giant planets. We must leave this challenging goal to future papers, unfortunately.

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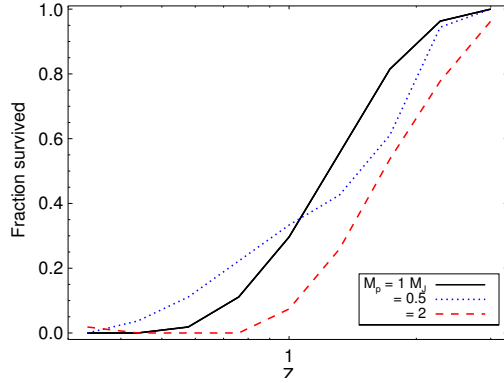


Figure 4. Planet survival probability versus Z for three different planet's masses, as labelled on the figure.

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