Metallicity of the Massive Protoplanets Around HR 8799 If Formed by Gravitational Instability

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Abstract
The final composition of giant planets formed as a result of gravitational instability in the disk gas depends on their ability to capture solid material (planetesimals) during their 'pre-collapse' stage, when they are extended and cold, and contracting quasi-statically. The duration of the pre-collapse stage is inversely proportional roughly to the square of the planetary mass, so massive protoplanets have shorter pre-collapse timescales and therefore limited opportunity for planetesimal capture. The available accretion time for protoplanets with masses of 3, 5, 7, and 10 Jupiter masses is found to be $7.82 \times 10^4$, $2.62 \times 10^4$, $1.17 \times 10^4$ and $5.67 \times 10^3$ years, respectively. The total mass that can be captured by the protoplanets depends on the planetary mass, planetesimal size, the radial distance of the protoplanet from the parent star, and the local solid surface density. We consider three radial distances, 24, 38, and 68 AU, similar to the radial distances of the planets in the system HR 8799, and estimate the mass of heavy elements that can be accreted. We find that for the planetary masses usually adopted for the HR 8799 system, the amount of heavy elements accreted by the planets is small, leaving them with nearly stellar compositions.

Key Words PLANETARY FORMATION; PLANETESIMALS; ACCRETION; ABUNDANCES, INTERIORS

arXiv:0911.5003v1 [astro-ph.EP] 26 Nov 2009
1 Introduction

The recent discoveries of wide-orbit massive protoplanets by direct imaging (Kalas et al., 2008; Marois et al., 2008) have presented a new type of gaseous planets that giant planet formation theories must be able to explain. Work regarding possible formation scenarios has already been demonstrated by several groups (e.g., Dodson-Robinson et al., 2009b; Nero and Bjorkman, 2009). Systems with massive gaseous planets at large radial distances offer a challenge for theorists mainly because they cannot be explained easily by the core accretion model, the standard model for giant planet formation (e.g., Cameron, 1978; Pollack et al., 1996). The core accretion model fails to form giant planets at large radial distances in situ due to the low surface density and the extremely long accretion timescale (Ida and Lin, 2004; Dodson-Robinson et al., 2009b). As a result, a more detailed investigation of giant planet formation scenarios seems to be required.

In addition, the increasing number of transiting planets provides information regarding the planetary mean densities, and therefore, their compositions. Giant planet formation theories are also required to explain the planets’ observed properties, and when possible, provide predictions that can be tested with future observations and upcoming data. Since the heavy element masses of planets can be estimated for transiting planets, further investigation and more detailed understanding of the origin of the heavy elements and the cause for the large variety in heavy elements enrichments observed (e.g., Guillot et al., 2007) is desirable.

While the core accretion model offers an enrichment with heavy elements that is coupled to the formation process (e.g., Pollack et al., 1996; Hubickyj et al., 2005), in the gravitational instability model (Cameron, 1978; Boss, 1997) the planet’s enrichment with solids is so far considered as an independent part of the actual formation mechanism. In the disk instability model giant protoplanets are initially formed with stellar compositions, and can be enriched with heavy elements after their formation by accretion of planetesimals (e.g., Helled et al., 2006). The total mass of solids that can be accreted depends on the planetary mass, its radial distance, the available solid material for capture, and the protoplanet’s efficiency in accreting the solid planetesimals (Helled and Schubert, 2009).

A gravitationally unstable condensation of a few Jupiter masses in a protoplanetary disk evolves through three phases (DeCampli and Cameron, 1979; Bodenheimer et al., 1980). First, it contracts quasi-statically with cool internal temperatures on the order of a few hundred K, with hydrogen in molecular form, and with radii a few thousand times the present Jupiter radius. Second, once the central temperature reaches about 2000 K, the H\textsubscript{2} dissociates and initiates a dynamical collapse of the entire planet, ending only when the radius has decreased to a few times the present Jupiter radius. Third, it contracts and cools on the long time scale of \(\sim 10^9\) yr. The first phase is the crucial one for the capture of solids, and the time scale of this phase, which is about \(4 \times 10^5\) yr for 1 Jupiter mass, determines the amount of material that can be captured. As the protoplanets contract quasi-statically during this phase, planetesimals in their feeding zone can be slowed down by gas drag, and get absorbed in the planetary envelopes (e.g., Helled and Schubert, 2009). As a protoplanet contracts, fewer planetesimals pass through its envelope, and instead of being accreted they get ejected from the protoplanet’s vicinity. Efficient planetesimal accretion ends once the central temperature reaches \(\sim 2000\) K and molecular hydrogen begins to dissociate.

Whether gaseous protoplanets can form as a result of a local gravitational instability in a protoplanetary disk is still a matter of debate. The majority of theoretical and numerical work suggests that the gravitational instability scenario for planet formation is rather unlikely, at least at relatively small radial distances (e.g., Rafikov, 2007; Cai et al., 2009). Other results suggest that protoplanetary disks can break into gaseous protoplanets (e.g., Boss, 1997), although this may be limited to special conditions (Mayer et al., 2007). The extrasolar giant planets observed by direct imaging (Kalas et al., 2008; Marois et al., 2008) have raised the suggestions that such massive gaseous planets at large radial distances were formed as a result of gravitational instabilities (Dodson-Robinson et al., 2009b; Nero and Bjorkman, 2009). The fact that HR 8799 host star is found to be metal-poor ([Fe/H]=-0.47) supports the idea that its planetary system was formed via disk instabilities. More advanced numerical simulations with longer integration times and further theoretical work seem to be required before a robust conclusion regarding this formation mechanism and its limitations can be made. While recent theoretical work (Boley, 2009; Rafikov, 2009; Nero and Bjorkman, 2009) suggests that gravitational instability can form planets only at distances greater than 50-100 AU, it is possible that
these planets can migrate inward as a result of interactions with the disk, after formation. Thus in this paper we use the working hypothesis that massive gaseous planets presently at radial distances > 20 AU could have formed as a result of gravitational instability. Below we investigate the process of heavy element enrichment via planetesimal capture for the planetary system HR 8799.

2 Enriching the Protoplanets with Solids

2.1 Pre-Collapse Evolution

Even under the assumption that gaseous protoplanets can form as a result of gravitational instability in the disk, a complication comes from the fact that the initial states (configurations) of the formed protoplanets are unknown. Numerical simulations of protoplanetary disks often report different configurations for the newly formed gaseous objects. Simulations made by Boss (e.g., Boss, 1997, 2002) typically result in colder and less dense objects than the ones found by Mayer and collaborators (Mayer et al., 2002, 2004, 2007). Both of these groups present denser and warmer initial configurations than the ones used in previous investigations (DeCampli and Cameron, 1979; Bodenheimer et al., 1980).

We take the protoplanets to be spherical and static objects. The initial radius must be less than the Hill radius. We assume that the planets were formed at their observed locations namely, 24, 38, and 68 AU, or at least reached those positions early in their evolution. The planetary masses for the HR 8799 system are estimated to fall in the range 5-13 Jupiter masses (Marois et al., 2008); we consider planets with masses between 3 and 10 Jupiter masses. We take the initial configuration such that the protoplanet is gravitationally bound at a radial distance of 24 AU around a 1.5 $M_{\odot}$ star, the minimal radial distance of the HR 8799 system.

Typically, the chosen initial states of protoplanets can be taken as arbitrary, based on the argument that after a relatively short time the planets retain no memory of their initial states (DeCampli and Cameron, 1979; Marley et al., 2007; Helled and Schubert, 2009). However, if the evolutionary time is short, as in the case for massive gaseous protoplanets, different initial configurations can result in different pre-collapse timescales. While the different initial states do not affect much the global evolution of the planets, they may influence the accretion process. This issue is further discussed in section 3.

Our baseline case for the initial model is a 'cold start' in which the protoplanets are as extended and cold as possible (and yet gravitationally bound), resulting in the maximal pre-collapse contraction time, and therefore the longest available time for planetesimal accretion. We then follow the planetary evolution up to the point when the central temperature reaches about 2000 K and the dynamical collapse begins. The four standard equations of stellar structure are solved (Henyey et al., 1964): hydrostatic equilibrium, mass distribution, energy conservation, and radiative or convective transport. The energy source is gravitational contraction of the gas alone. The surface boundary condition is that of an isolated stellar photosphere. Calculated surface temperatures turn out to be a few tens of degrees K, comparable to disk temperatures at the distances considered; thus disk irradiation effects will not have significant influence on the boundary condition. In addition, as we show below, efficient planetesimal accretion occurs when the protoplanets have already evolved to denser and warmer configurations with the surface temperatures being higher than the disk temperatures. As a result, the disk temperature becomes insignificant by the time planetesimals can be accreted. No central solid core is present. The low-temperature opacities, which are dominated by grains with an interstellar size distribution, are obtained from Pollack et al. (1985) and Alexander and Ferguson (1994). The equation of state is based on the tables of Saumon et al. (1995). The accreted mass of solid planetesimals is computed during the pre-collapse evolution.

Table 1 summarizes the initial states for planetary masses between 3 and 10 $M_J$ ($M_J$ being Jupiter’s mass). The last column provides the pre-collapse time-scale for each mass. Figure 1 presents the evolution of protoplanets with masses of 3, 5, 7, and 10 Jupiter masses. As can be seen from the figure, more massive protoplanets have shorter pre-collapse time-scales. The initial radius increases with increasing planetary mass, as more massive objects can be more extended and still be gravitationally bound due to stronger gravity. The central temperature however, is higher for more massive bodies.
It is possible that massive clumps (∼ 10 M_J) do not form directly by a single gravitational instability, but are formed as a result of substantial gas accretion and possibly mergers of smaller clumps. In such a case the effective pre-collapse contraction timescales of the massive protoplanets would be longer than presented here and comparable to the timescales which correspond to smaller objects. As a result, the final metallicity of the massive protoplanets would be determined by the planetesimal accretion efficiency of the smaller protoplanets. However, as we show below, for the range of masses we consider, there is no significant difference in the resulting metallicity of the protoplanets.

Our evolutionary model assumes a non-rotating clump, while in reality giant gaseous protoplanets formed by gravitational instabilities are likely to have some angular momentum. Most of the interior of the protoplanet is convective, and its effect will be to transport angular momentum outward, on a convective turnover time scale, and drive the distribution of angular momentum toward uniform rotation. The resulting structure, which still needs to be investigated in detail, will have most of the mass in slow rotation, and a relatively small fraction of the mass in an outer subdisk. The effective mass of the protoplanet, which represents the low-angular momentum portion, will be somewhat lower than the total mass we consider and will therefore have a somewhat longer contraction time. Also, the formation of the subdisk can result in a longer available time for solid accretion since it is likely to exist after the dynamical collapse, providing a source of gas drag that can lead to additional accretion. In addition, planetesimals in such a disk can collide and lead to the formation of satellites (Helled et al., 2006).

2.2 Planetesimal Accretion

The amount of solid material (heavy elements) accreted by a gaseous protoplanet depends on the available mass for capture in the planet’s feeding zone, and the protoplanet’s efficiency in accreting the solid planetesimals. The planetesimal accretion rate is given by (Safronov, 1969)

\[ \frac{dm}{dt} = \pi R_{\text{capture}}^2 \sigma \Omega F_g, \]

where \( R_{\text{capture}} \) is the protoplanet’s capture radius (see Helled et al., 2006 for details), \( \sigma \) is the solid surface density, and \( \Omega \) is the protoplanet’s orbital frequency. We take the gravitational enhancement factor \( F_g \) (Greenzweig and Lissauer, 1990) as unity, providing a lower bound estimate for the capture rate. It should be noted, that Safronov’s formulation (equation 1) assumes that the protoplanet is rotating around the star with the same angular velocity as the gas. The protoplanet’s motion relative to the gas is in the z-direction, due to its inclined orbit. The formulation applies when assuming that the planetary orbit goes from the “bottom” of the disk, through the midplane and to the “top” of the disk in half an orbit, so in every orbit the protoplanet goes the entire thickness of the disk encountering solid surface density \( \sigma \) (g cm\(^{-2}\)).

We follow the evolution of the protoplanet, and at each stage we calculate planetesimal trajectories with increasing impact parameters, accounting for gas drag and gravitational forces, to find \( R_{\text{capture}} \). Ablation and fragmentation of planetesimals are included in the trajectory calculation. We determine the largest impact parameter for which planetesimal capture is possible. For this trajectory the planetesimal’s closest distance of approach to the protoplanet’s center is defined as the capture radius, \( R_{\text{capture}} \) (see further details in Helled et al., 2006, Helled and Schubert, 2009 and references therein). It should be noted that the evolution calculation does not account for the accreted material. However, as we show below, in all the cases considered in this work, the amount of solids being captured is negligible compared to the planetary mass and therefore is unlikely to affect the planetary evolution. In addition, we find that the solid material is deposited in the denser inner regions which are convective, and therefore the accreted material is not expected to change the opacity near the planet’s photosphere. As a result, the larger concentration of heavy elements would increase the opacity but not affect the convective stability, so that the expected thermal evolution would be similar. More details on the effect of planetesimal accretion on the thermal evolution, including the effect on the energy budget of the protoplanet, can be found in Helled et al. (2006).

At early stages of the planetary evolution, the capture radius can be substantially smaller than the physical radius of the protoplanet due to the low density in the upper envelope, and the fact that the planetesimal must pass through denser inner regions to encounter enough gas drag, lose kinetic energy, and
get captured by the protoplanet. Recently, major progress in understanding planetesimal formation has been achieved. Although the process that leads to planetesimal formation is still debated, there seems to be a general agreement that planetesimals have larger initial sizes than previously thought. Two independent groups have shown recently that large planetesimals, of about 100 km in size, are formed directly from solid particle concentrations, therefore 'skipping' sizes of hundred meters and a few kilometers (e.g., Johansen et al., 2007; Cuzzi et al., 2008). Further support for this idea came from yet another group that showed that planetesimals must form in big sizes in order to fulfill the constraints coming from the asteroid belt size-frequency distribution (Morbidelli et al., 2009). We consider planetesimals with sizes of 1, 10, and 100 km. The planetesimals are taken to be composed of a mixture of ice, silicates and CHON with an average density of 2.8 g cm$^{-3}$ (see Pollack et al., 1996, and Helled et al., 2006 for details). Although planetesimals are preferentially captured toward the center of the protoplanet, their settling toward the center to form a core is not considered.

As shown below, the accreted mass is rather sensitive to the assumed planetesimals’ sizes. Planetesimals with sizes larger than 100 km will be even harder to accrete, resulting in lower captured mass than the results presented. Smaller planetesimals than the ones considered in this work will be captured more easily, and would lead to larger enrichment with heavy elements. Practically, the disk is likely to have a size distribution for the planetesimals, which can change with time (collisions, breakup) and radial distance. For simplicity, and since the real sizes of planetesimals and their time/radial dependence are not well constrained, we consider only three planetesimal sizes.

Naturally, the large orbital distances in the HR 8799 planetary system (Marois et al., 2008) lead to smaller enrichment due to the decrease in the solid surface density with radial distance, and slower accretion rate due to the dependence on the orbital frequency (see equation (1) and Helled and Schubert, 2009). We adopt the disk model presented by Dodson-Robinson et al. (2009b); this stellar-heated disk has a Toomre Q value $\sim 1.5$ around a 1.5 M$_\odot$ star. The surface density of the disk goes $\propto a^{-12/7}$ with $a$ being the radial distance from the star (see their eq. 6): the disk mass is about 30% of the system mass. The solid/gas ratio is taken from the disk model of Dodson-Robinson et al. (2009a), which takes into account the details of the chemistry at each distance. The distribution of the solid surface density is plotted in Figure 1 of Dodson-Robinson et al. (2009b). The solid surface densities at 24, 38, and 68 AU are found to be 7, 3, and 1 g cm$^{-2}$, respectively.

The planetesimal velocities far from the protoplanet are taken with respect to the protoplanet, i.e., the protoplanet is assumed to be at rest relative to the planetesimals, with the velocities taken to be 10% of the Keplarian velocities, in agreement with estimates based on detailed 3-body interactions (e.g., Greenzweig and Lissauer, 1990). The velocities are therefore set to $7.44 \times 10^4$, $5.92 \times 10^4$, and $4.42 \times 10^4$ cm s$^{-1}$, for 24, 38, and, 68 AU, respectively. Once the planetesimal velocities for the different radial distances are set, the protoplanets’ cross section for planetesimal capture, and the mass accretion rate can be computed. Gravitational potential fluctuations in the disk as a result of gravitational instability could in fact stir up the planetesimal velocities to higher values. The result would be a reduction in the planet’s cross section for capture.

Figure 2 shows the capture radii for 3 and 10 Jupiter mass protoplanets as a function of time. The black, blue, and red curves correspond to radial distances of 24, 38, and 68 AU, respectively. The dotted, dashed, and dashed-dotted curves represent 1, 10, and 100 km-sized planetesimals, respectively. As expected, larger planetesimals result in smaller capture radii. 100 km-sized planetesimals cannot be captured at very early stages of the planetary evolution due to low densities and temperatures at the upper envelopes of the protoplanets. A more detailed analysis on the behavior of the capture radius with time can be found in Helled et al. (2006). The capture radius increases with increasing radial distance due to lower planetesimal velocities. However, as we show below, due to the slow accretion rate farther from the star, the mass that can actually be captured decreases with radial distance.
3 Results

Table 2 presents the captured planetesimal mass for all the cases considered. Larger planetesimals are harder to capture, and for all cases considered in this work the captured mass from 100 km-sized planetesimals is smaller than 1 $M_{\oplus}$. If planetesimals are indeed formed large, massive protoplanets could not be enriched with heavy elements via planetesimal capture. A 10 $M_J$ protoplanet is massive enough to have a large capture capture cross section, and therefore has a potential to capture a significant amount of solids. However, it has a very short pre-collapse stage and therefore, the final captured mass is substantially smaller than the available mass for accretion. Nevertheless, a 10 $M_J$ planet at 24 AU can capture about 90 $M_{\oplus}$ of heavy elements if planetesimals are 1 km in size. As the planetary mass decreases the gravitational pull decreases but the available time for planetesimal capture increases. As a result, a 3 $M_J$ protoplanet can accrete more solid material than one of 5 $M_J$.

To check the robustness of our result and its sensitivity to the initial model of the protoplanet, we run a test case in which we allow a more compact and hotter initial model for a 5 Jupiter mass object. The properties of the initial model are listed in Table 1 (5 $M_J$ - hot start). The accreted planetesimal mass for this case is given in Table 3. As can be seen from the table, the numbers do not change substantially and the trend found in the cold start case is certainly maintained. Although the pre-collapse timescale is shorter for protoplanets with a 'hot start', the accreted mass is nearly the same as for the cold start case. This is due to the fact that at the early stages of the cold start evolution the densities are low and only a very small fraction of planetesimals can be accreted before the hot start densities are reached. While the exact values of the accreted mass can change for different chosen initial conditions, the conclusion that massive protoplanets cannot accrete a significant amount of heavy elements at wide orbits, and that the mass decreases substantially with increasing planetesimal size is robust with regard to the assumed initial condition for the protoplanet.

4 Discussion and Conclusions

We investigate the possibility of heavy element enrichment for the planetary system HR 8799. We consider planetary masses of 3, 5, 7 and 10 $M_J$, with radial distance of 24, 38, and 68 AU. We find that planetesimal accretion is relatively inefficient for such a system due to main two reasons: First, massive protoplanets have relatively short precollapse stages, and therefore, have limited time for planetesimal capture. Second, the accretion rate is low at large radial distances due to its dependence on the solid surface density and orbital frequency (both decreasing with radial distance). Farther from the star planetesimal velocities are lower, but the accretion time-scale is substantially longer.

Smaller planetesimals can be accreted more efficiently, and if planetesimal sizes are of the order of $\sim 1$ km, solid material between a few and tens of $M_{\oplus}$ can be captured. However, if planetesimals are formed with initial sizes of $\sim 100$ km or larger, the accreted mass is negligible. We therefore conclude that under such conditions wide-orbit gaseous planets, if formed via gravitational instability, will have nearly stellar compositions.

The capture cross-section used in this work was calculated taking the gravitational enhancement factor $F_g$ which corrects for the three-body effects (see Greenzweig and Lissauer 1990 for details) as unity. As a result, the accreted mass presented here should be taken as a lower bound. The total mass of solids in the protoplanet’s feeding zone, which represents the maximum solid mass available for accretion, can be up to 2-3 $M_J$, increasing with radial distance. However, it is unlikely that this available mass can actually be accreted due to the low accretion rate (see Helled and Schubert, 2009 for details) unless it is found that a significant gravitational focusing occurs. Detailed calculations of the gravitational enhancement factor for extended massive protoplanets with gas drag included seem to be required before a robust estimate for the upper bound of the accreted mass can be made.

Our results suggest that massive protoplanets at wide orbits will have metallicity similar to their parent star. This conclusion does not depend on the stellar metallicity. Naturally, protoplanets around metal-rich stars will contain more high-Z material in their interiors due to the larger fraction of heavy elements (higher
dust-to-gas ratio), but as we show here, an increase in the available solid material typically does not lead
to further enrichment due to the low accretion rate. Protoplanets around stars with lower metallicity than
considered here, will have a smaller fraction of heavy elements due to their initial composition which is
metal-poor, and the fact that planetesimal accretion is inefficient as a result of the long accretion timescale
and the low solid surface density. Our suggestion that massive gaseous planets at large radial distances will
have stellar compositions is therefore independent of stellar metallicity.

Our conclusion that massive protoplanets ($\geq 3 \, M_J$) will have relatively low enrichments in heavy elements
is valid under the assumption that the high-Z material is captured during the pre-collapse stage in the form of
solid planetesimals. It is possible however, that another enrichment mechanism for massive gaseous planets
exists. For example, it may be possible that gaseous protoplanets are enriched with heavy elements from 'birth'. Disk fragments form at the corotation of dense spiral waves (Durisen et al. 2008) which can be
enhanced with heavier elements (e.g., Haghighipour and Boss 2003, Rice et al. 2004) leading to formation of
enriched fragments. In that case, solid concentrations are achieved at the locations where fragmentation is
most likely to occur, and the formed protoplanets will be metal-rich relatively to their host star. In addition,
simulation of solids in disks show that regions in the disk can become highly enriched with solid material
as a result of vortices in the disk (e.g., Klahr and Bodenheimer, 2006), although such vortices are likely to
be destroyed in self-gravitating disks (Mamatsashvili and Rice, 2009). In any case, forming gaseous massive
protoplanets which are enriched with heavy elements from birth is possible, and as a result massive gaseous
protoplanets at large radial distances could contain a significant amount of heavy elements. It would be
desirable to investigate whether enrichment from birth can be distinguished from enrichment at later stages
(planetary evolution, internal structure, etc.), and we hope to address this issue in future work. An even
more important issue that needs to be addressed to make future progress on this problem is a detailed study
of planetesimal formation and collisional evolution in the 50–100 AU region of a gravitationally unstable
disk.

Given the assumption that the planets around HR 8799 formed from near-stellar composition, a question
arises as to the observable metallicity in the present atmospheres. Even if there is added planetesimal
material it tends to be deposited deep inside the planet, and a substantial fraction of it would condense out
and form a solid core (Helled et al., 2008). Also, to a lesser extent, the grains in the original composition
of the planet would tend to settle out, and at least the rock component could be added to the core. The
heavy element material not in the core would have been mixed by convection before the present time. These
considerations suggest a slight depletion in heavy elements in the envelope of the planet as compared with the
star. However numerous additional processes, such as cloud formation and possible core erosion, affect the
atmosphere between the early phase studied here and the present time. Thus it is difficult to make precise
predictions. In the limiting case where the planet has been completely mixed and has uniform composition
at the present time, a typical case (38 AU, 10 km planetesimals, 7 $M_J$), the added solid mass is only 2.9 $M_\oplus$
compared to a total mass of 2226 $M_\oplus$. Thus even with some enhancement as discussed earlier, the difference
between planetary and stellar metallicity would be negligible. Even in the case of the most-enriched planet,
the fraction of solid material added is only 4% by mass.

**Acknowledgments**

R. H. acknowledges support from NASA through the Southwest Research Institute. P. B. acknowledges
support from the NASA Origins grant NNX08AH82G.

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Figure 1: Pre-collapse evolution of 3, 5, 7 and 10 Jupiter masses. The luminosity, radius, and central temperature as a function of time are presented.
Figure 2: Capture radius vs. time for 3 (top) and 10 (bottom) M_J protoplanets. The black, blue, and red curves correspond to radial distances of 24, 38, and 68 AU, respectively. The dotted, dashed, and dashed-dotted curves represent 1, 10, and 100 km-sized planetesimals, respectively.
| Planetary Mass (M_J) | Initial Radius (×10^{13} cm) | Central Temperature (K) | Central Density (×10^{-10} g cm^{-3}) | τ pre-collapse (years) |
|----------------------|-----------------------------|------------------------|----------------------------------------|--------------------------|
| 3                    | 3.16                        | 188                    | 3.83                                   | 7.82×10^4                |
| 5                    | 3.49                        | 302                    | 5.70                                   | 2.62×10^4                |
| 5 - hot start        | 0.83                        | 1353                   | 659.9                                  | 1.69×10^4                |
| 7                    | 3.23                        | 499                    | 14.0                                   | 1.17×10^4                |
| 10                   | 4.19                        | 512                    | 7.43                                   | 5.67×10^3                |

Table 1: Physical properties of the initial models for the four considered planetary masses. The fifth column gives the pre-collapse time-scale.
Table 2: Captured mass for 3, 5, 7, and 10 Jupiter masses protoplanets with 'cold start'. For comparison, the initial complement of heavy elements, in the special case of solar abundances, in a 5 M\(_J\) planet is about 30 M\(_\oplus\).
| $r$ (AU) | $\sigma$ (g cm$^{-2}$) | $v_{\text{inf}} \times 10^4$ (cm s$^{-1}$) | planetesimal size (km) | Captured Mass (M$_{\oplus}$) |
|---|---|---|---|---|
| 24 | 7 | 7.44 | 1 | 18.4 |
| 24 | 7 | 7.44 | 10 | 9.2 |
| 24 | 7 | 7.44 | 100 | 1.6 |
| 38 | 3 | 5.92 | 1 | 4.3 |
| 38 | 3 | 5.92 | 10 | 2.3 |
| 38 | 3 | 5.92 | 100 | 0.6 |
| 68 | 1 | 4.42 | 1 | 0.7 |
| 68 | 1 | 4.42 | 10 | 0.4 |
| 68 | 1 | 4.42 | 100 | 0.1 |

Table 3: Test case: captured mass for 5 Jupiter masses protoplanets with 'hot start'.