Hot-start Giant Planets Form with Radiative Interiors

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Abstract

In the hot-start core accretion formation model for gas giants, the interior of a planet is usually assumed to be fully convective. By calculating the detailed internal evolution of a planet assuming hot-start outer boundary conditions, we show that such a planet will in fact form with a radially increasing internal entropy profile, so that its interior will be radiative instead of convective. For a hot outer boundary, there is a minimum value for the entropy of the internal adiabat $S_{\text{min}}$ below which the accreting envelope does not match smoothly onto the interior, but instead deposits high entropy material onto the growing interior. One implication of this would be to at least temporarily halt the mixing of heavy elements within the planet, which are deposited by planetesimals accreted during formation. The compositional gradient this would impose could subsequently disrupt convection during post-accretion cooling, which would alter the observed cooling curve of the planet. However, even with a homogeneous composition, for which convection develops as the planet cools, the difference in cooling timescale will change the inferred mass of directly imaged gas giants.

Key words: planets and satellites: formation – planets and satellites: gaseous planets – planets and satellites: interiors

1. Introduction

Giant planets may form from core accretion, in which runaway gas accretion occurs onto a $\sim 10 M_\oplus$ core, or from direct collapse from the gas disk (see Helled et al. 2014 for a review). A number of observational constraints on how gas giant planets form are becoming available, both in our solar system and in exoplanetary systems. Young massive giant planets have been directly imaged (Bowler 2016), revealing their thermal state $\sim 10^3$ years after formation and the composition of their atmospheres. Exoplanet surveys have measured occurrence rates and orbital architectures of planetary systems containing gas giants (e.g., Clanton & Gaudi 2016). In the solar system, a recent example is the precise measurements of Jupiter’s gravitational moments by Juno (Bolton et al. 2017), suggesting the core may be diluted, expanded to $\gtrsim 0.3$ of Jupiter’s radius (Wahl et al. 2017). This indicates either that the core can be mixed upward during evolution, or is telling us about the distribution of heavy elements at formation. This variety of observations motivates continued theoretical work on the physics of gas giant formation.

A major uncertainty in the core accretion scenario is the efficiency of the shock that forms at the surface of the planet during runaway accretion (Marley et al. 2007). Depending on how much of the gravitational energy of the infalling matter is radiated away at the shock, the luminosity of the planet after formation can differ by orders of magnitude, leading to uncertainty in derived planet masses (Marley et al. 2007; Spiegel & Burrows 2012; Marleau & Cumming 2014). Recent work has suggested, however, that a hot start is more likely than a cold start. Marleau et al. (2017) carried out 1D radiation-hydro-simulations of the shock and found that a significant fraction of the gravitational energy is incorporated into the planet (see also Szulágyi & Mordasini 2017). Berardo et al. (2017) studied the growth of giant planets treating the shock temperature as a free parameter. They found that the cold starts of Marley et al. (2007; based on the simulations of Hubickyj et al. 2005) required very low boundary temperatures: close to the disk temperature and lower than the photospheric temperature of the planet. Owen & Menou (2016) studied growth by disk accretion and found hot starts when the boundary layer thickness exceeded a critical value.

In this Letter, we present detailed models of the runaway accretion phase of gas giant growth under the assumption of a hot start. Previous core accretion models by Pollack et al. (1996), Bodenheimer et al. (2000), Hubickyj et al. (2005), and Lissauer et al. (2009) assumed cold outer boundaries. Mordasini (2013) calculated hot-start models by stepping through pre-computed planet models that assumed a constant internal luminosity (Mordasini et al. 2012), and so did not follow the effect of accretion on the internal structure. Here, we use the Modules for Experiments in Stellar Astrophysics (MESA) code (Paxton et al. 2011, 2013, 2015) to calculate the internal structure during accretion with a hot-start boundary condition. We show that the planet forms in successive layers of increasing entropy3, inhibiting convection and giving a radiative interior (this possibility was discussed by Mordasini et al. 2012 based on previous work on accretion onto low-mass stars; e.g., Prilnik & Livio 1985). In Section 2, we discuss the entropy of matter deposited by the accreting envelope and show that the evolution of the shock temperature with time determines whether the growing planet is convective or radiative. In Section 3, we present numerical models with MESA that follow the planet growth and subsequent cooling. We discuss the implications of our results in Section 4.

2. The Entropy of Matter Deposited by the Accreting Envelope

During runaway gas accretion, infalling matter is decelerated at an accretion shock at the planet’s surface (Bodenheimer et al. 2007; based on the simulations of Hubickyj et al. 2005) required very low boundary temperatures: close to the disk temperature and lower than the photospheric temperature of the planet. Owen & Menou (2016) studied growth by disk accretion and found hot starts when the boundary layer thickness exceeded a critical value.

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The post-shock conditions depend on how much of the accretion energy is radiated away at the shock; this sets the post-shock pressure \( P_s \) and temperature \( T_0 \) (e.g., Marleau et al. 2017). Berardo et al. (2017) studied the subsequent evolution of the accreting matter as it settles into the envelope of the planet. They showed that for sufficiently large \( T_0 \), the radiative envelope is not able to accommodate the large contrast in entropy between the post-shock matter with entropy \( S_0 \) and the interior with entropy \( S_i \) (a similar result was found for accreting protostars by Stahler 1988). The entropy in the envelope decreases to a minimum value \( S_{\text{min}} \) and the accreting envelope effectively deposits matter with entropy \( S_{\text{min}} \) onto the growing interior. This contrasts with lower values of \( T_0 \) for which the entropy in the radiative envelope decreases from \( S_0 \) to \( S_i \) and joins smoothly onto the interior profile (Berardo et al. 2017 referred to this as the “stalling” regime as the cooling rate of the interior is slowed under these conditions).

The entropy \( S_{\text{min}} \) depends on the boundary temperature \( T_0 \), the accretion rate \( \dot{M} \), and the planet mass \( M \) and radius \( R \). Figure 1 shows the value of \( S_{\text{min}} \) as a function of \( T_0 \) and \( M \) for typical values of \( M \) and \( R \). We calculate \( S_{\text{min}} \) as described in Berardo et al. (2017).\(^4\) We construct steady-state models of the accreting envelope, successively lowering the luminosity at the surface until the luminosity at the base of the envelope goes to zero. The entropy at the base of this lowest luminosity envelope is \( S_{\text{min}} \).

Figure 1 shows that, depending on how \( T_0 \) changes as the planet increases in mass, \( S_{\text{min}} \) could either increase or decrease over time, which has implications for the internal structure. If \( S_{\text{min}} \) decreases with time, low entropy matter is deposited on top of high entropy matter. This situation is unstable to convection, and so we expect the growing planet to have a convective interior. If \( S_{\text{min}} \) increases with time, the planet grows in layers of successively increasing entropy, inhibiting convection and resulting in a radiative interior.

How do we expect \( T_0 \) to evolve as the planet grows? Berardo et al. (2017) assumed constant \( T_0 \) during accretion to assess how the choice of \( T_0 \) affected the outcome of accretion. Figure 1 shows that in that case \( S_{\text{min}} \) decreases with increasing planet mass, so that the growing planet is always convective. However, in reality we expect the shock temperature to evolve as accretion proceeds. The surface temperature can be written as (Mordasini 2013)

\[
T_0^4 = \frac{1}{4\pi R^2\sigma}(L_p + \eta L_{\text{accretion}}),
\]

where \( L_p \) is the internal luminosity and \( L_{\text{accretion}} \) the accretion luminosity \( L_{\text{accretion}} = GM\dot{M}/R \). The parameter \( \eta \) measures the efficiency with which the shock radiates (Prialnik & Livio 1985; Hartmann et al. 1997; Mordasini 2013). If the shock radiates away all of the accretion luminosity, then \( \eta = 0 \), corresponding to a cold start. If instead the accretion energy is not radiated away but advected into the planet, we have \( \eta = 1 \) and a hot start. Assuming \( L_{\text{accretion}} \gg L_p \), the hot-start temperature is

\[
T_0 \approx 1850 \text{ K} \left( \frac{M}{10^{-3} M_\odot} \right)^{1/4} \left( \frac{M}{M_\odot} \right)^{1/4} \left( \frac{R}{2 R_J} \right)^{-3/4},
\]

where we scale to the values of \( M \) and \( R \) in Figure 1. We see from Figure 1 that the corresponding value of \( S_{\text{min}} \) is \( \approx 9.5 \, k_B/m_p \). Provided that the internal entropy of the planet at the onset of runaway accretion is \( S_i \lesssim 9.5 \, k_B/m_p \), the accretion will be in the hot regime.

As the planet grows in mass, and assuming \( L_{\text{accretion}} \gg L_p \), Equation (2) gives \( T_0 \propto M^{1/4} R^{-3/4} \), or

\[
\frac{d \ln T_0}{d \ln M} = \frac{1}{4} \left( \frac{3}{4} \frac{d \ln R}{4 d \ln M} \right)
\]

A curve of constant \( S_{\text{min}} \) on the other hand has \( d \ln T_0/d \ln M \big|_{S_{\text{min}} \text{ const}} \approx 0.1 \) (the slope of the black contours in Figure 1). We see that as long as \( d \ln R/d \ln M \) is not too large (\( \lesssim 0.2 \)), so that \( d \ln T_0/d \ln M > d \ln T_0/d \ln M \big|_{S_{\text{min}} \text{ const}} \) will increase over time. We show in the next section that this is indeed the case in time-dependent models, so that the interior of the forming giant planet is radiative.

3. Time-dependent Simulations of Hot Starts

We use the MESA stellar evolution code (Paxton et al. 2011, 2013, 2015; version 8118) to compute a time-dependent model of an accreting gas giant with hot-start boundary conditions. We start with a 0.2 \( M_\odot \) planet with internal entropy \( S_i = 9.5 \, k_B/m_p \) (guided by the models of Mordasini 2013), hydrogen, helium, and metal fractions of 0.73, 0.25, 0.02, respectively, and a 10 \( M_\odot \) core of density 10 g cm\(^{-3} \). We accrete at a constant rate of \( 10^{-3} \, M_\odot \, \text{yr}^{-1} \) (Lissauer et al. 2009) until the planet reaches 10 \( M_\odot \). During accretion, we set the surface pressure to the sum of the ram pressure and photospheric pressure

\[
P_0 = \frac{M}{4\pi R^2} \left( \frac{2GM}{R} \right)^{1/2} + P_{\text{photo}}
\]

(Mordasini et al. 2012), and the temperature \( T_0 \) according to Equation (1) with \( \eta = 1 \). To avoid convergence issues associated with the onset of accretion, we ramp up the surface temperature

\(^4\) Code available at https://github.com/andrewcumming/gasgiant.
linearly from its initial value in the $0.2M_J$ model to $T_0$ during accretion of the first $0.2M_J$ (the first $\approx 6 \times 10^4$ years).

3.1. Evolution of the Shock Temperature and Radius

The time evolution of the shock temperature $T_0$ is shown as the orange curve in Figure 1. The radius evolved first as a fully convective object, decreasing as mass increased from an initial value of $2.1R_J$. Around a mass of $M = 1.5M_J$ it reached a minimum of $1.7R_J$, and then began to increase as the structure of the planet became predominantly radiative, back to $2R_J$ at $M = 10M_J$. Fitting a power law to the increasing radius gives $d\ln R/d\ln M \approx 0.1$. Equation (3) then predicts $d\ln R_0/d\ln M \approx 0.15$, which is in good agreement with the increase of $T_0$ with $M$ (a power-law fit to the curve in Figure 1 gives $d\ln R_0/d\ln M \approx 0.18$).

As discussed in Section 2, when $T_0$ increases with mass steeper than $d\ln T_0/d\ln M \approx 0.1$, we expect $S_{\text{min}}$ to increase with time, and the internal structure to be radiative. The increasing radius with mass indicates this. Studies of the response of stars to accretion have shown that whereas fully convective objects shrink with increasing mass, radiative stars increase in radius, consistent with our results (Prialnik & Livio 1985; Hjellming & Webbink 1987; Soberman et al. 1997).

3.2. Internal Entropy Profile

Figure 2 shows how the entropy profile evolves with time as the mass of the planet grows. The entropy at a given mass coordinate $m$ remains constant as the planet increases in total mass $M$, and the entropy profile is such that entropy increases with $m$, i.e., increases outward in the interior.

The increasing entropy profile $S(m)$ is consistent with the expectation from Section 2 that the entropy deposited at the base of the accreting envelope increases over time. To test this idea, we calculated $S_{\text{min}}$ as described in Section 2 as a function of time (or equivalently total planet mass), using the values of $T_0$, $M$, and $R$ at each time step. The black dashed curve in Figure 2 shows $S_{\text{min}}$ as a function of planet mass. We see that it closely reproduces the internal entropy profile, showing that we can understand the growth of the planet as successive layers with entropy $S_{\text{min}}$. The timescale for radiative diffusion or thermal conduction is much longer than the accretion timescale, so that the entropy at a given mass coordinate remains unchanged as the planet grows.

Figure 3 shows the outer envelope in more detail. In the envelope, the entropy profile flattens, suggesting the onset of convection. Indeed, we see convection occurring in the envelope, indicated by the solid circles in the top panel of Figure 3. However, we note that the convection is irregular, with individual zones switching between convective and radiative as time proceeds (we have checked that this does not depend on our spatial resolution or time step). The value of entropy at which the envelope flattens corresponds to $S_{\text{min}}$. At higher pressures (that make up $\geq 99\%$ of the mass), the structure is radiative, with entropy decreasing to higher pressures.

Figure 2. Entropy profiles as a function of interior mass coordinate over time. Color indicates the age of the planet, going from orange (youngest) to blue (oldest) as the planet grows to 10 $M_J$. At the assumed constant accretion rate of $M = 10^{-3}M_J$ yr$^{-1}$, the time to accrete a given mass is $t \approx 3 \times 10^3$ year ($M/M_J$). The spike in entropy in each model is due to the outer radiative zone at the surface of the planet. The dashed black curve shows the calculated value of $S_{\text{min}}$ as a function of total mass (i.e., one value of $S_{\text{min}}$ for every time step), showing that the internal profile of the planet at the end of accretion is set by the history of $S_{\text{min}}$ during accretion.

Figure 3. Temperature and entropy profiles as a function of pressure during accretion. Color indicates the planet’s age as in Figure 3, going from orange (youngest) to blue (oldest) as the planet grows to 10 $M_J$. In the top panel, black points indicate where the planet is convective according to the Schwarzschild criterion.
3.3. Post-accretion Cooling

Although the internal structure is radiative during accretion, convection develops once accretion turns off and the planet begins to cool. Figure 4 shows the entropy profile at different times following the end of accretion. A convection zone develops at the surface (indicated by the region of constant entropy extending from the surface inward), and penetrates deeper over time until the whole planet becomes convective. For the $10\ M_J$ planet shown in Figure 4, it takes approximately $10^7$ years for the planet to become fully convective. For a $1\ M_J$ planet, the timescale is shorter, $\sim 10^6$ years.

The timescale for the convection zone to move inward can be understood in a similar way to cooling of fully convective planets, by treating the convection zone as a single zone with entropy $S$ (the “following the adiabats” approach; e.g., Fortney & Hubbard 2004). The luminosity leaving the convection zone depends on the opacity at the radiative-convective boundary (RCB) near the surface and is a function of the entropy and total planet mass, $L(S, M)$. The mass in the convection zone then evolves according to

$$\frac{dM_{\text{conv}}}{dt} = \frac{dS}{dt} = -\frac{L(S, M)}{M_{\text{conv}} T dS_0/dm}, \quad (5)$$

where $dS_0/dm$ is the gradient of the entropy profile $S_0(m)$ at the end of accretion, and $\bar{T}$ is the mass-averaged temperature in the convection zone. The convection zone entropy drops faster than a fully convective planet because it has a smaller mass and because it is cooler (it occupies the outer regions). We have integrated Equation (5) over time using $L(S, M)$ from Marleau & Cumming (2014) and find good agreement with MESA.

Luminosity, radius, and effective temperature are shown in Figure 5 for two planet masses and compared to fully convective hot starts calculated using MESA and from Burrows et al. (1997). The inwardly decreasing entropy means that the planet is more compact for its luminosity than a fully convective object. The differences are more pronounced at larger planet masses and earlier times. At 1 Myr, the luminosity is a factor of $\approx 2$ ($\approx 4$) times smaller and the radius $\approx 6\%$ ($\approx 25\%$) smaller than the convective hot start for $M = 2\ M_J$ ($10\ M_J$). These differences diminish over time until the planet becomes fully convective at $\sim 10^7$ years.

4. Discussion

We have shown that under the assumptions of hot-start core accretion, gas giants form with a radiative interior. For a sufficiently large shock temperature, the accreting envelope is in the heating regime of Berardo et al. (2017) and deposits material with entropy $S_{\text{min}}$ at its base. For hot-start boundary conditions, we find that $S_{\text{min}}$ increases with time during accretion (see the orange trajectory in Figure 1). The entropy...
profile when accretion ends is set by the time history of $S_{\text{min}}$ (Figure 2). Because $S_{\text{min}}$ increases outward, convection is inhibited and the interior is radiative.

The model we consider in this Letter has $\eta = 1$ (the hot-start limit) so that all of the accretion energy is deposited in the planet (Equation (1)), but we find that radiative interiors form for a range of values of $\eta$. For $M = 10^{-3} M_\odot$ yr$^{-1}$ ($M = 10^{-2} M_\odot$ yr$^{-1}$), models with $\eta \gtrsim 0.5$ ($\eta \gtrsim 0.05$) are in the hot regime. For lower values of $\eta$, the interior is fully convective as the envelope is able to match smoothly onto the interior adiabat during accretion (the stalling or cooling regimes of Berardo et al. 2017). We will explore the parameter space of $M$ and $\eta$ in future work.

During cooling, convection penetrates from the surface into the interior. The planet eventually becomes fully convective, at which point its internal entropy matches the initial entropy (here, taken to be $\approx 9.5 k_B/m_p$). The time to become fully convective is a few times shorter than the cooling time at this entropy (e.g., Figure 6 of Marleau & Cumming 2014), a timescale of $10^7$ years ($10^8$ years) for a $10 M_\oplus$ ($1 M_\oplus$) planet (Figure 4). At earlier times, the shape of the cooling curve is different from a traditional hot start, which is assumed fully convective from the beginning (Figure 5). The planet radius and luminosity are also smaller than a fully convective hot start with the same mass. Following the internal structure during formation is therefore crucial to make accurate inferences from direct imaging observations. For example, we find that at $\lesssim 10$ Myr after formation, a $10 M_\oplus$ planet is less luminous than a traditional hot start by a up to a factor of 4. Since $L \propto M^2$ approximately (e.g., Marleau & Cumming 2014), this translates to a derived mass larger by up to a factor of 2. The differences are smaller for lower masses and later times, e.g., tens of percent for $M = 2 M_\oplus$ and ages $\gtrsim 10$ Myr.

Our results may have implications for the heavy element distribution in giant planets. Heavy elements are deposited in the envelope before runaway accretion begins (Iaroslavitz & Podolak 2007; Helled & Stevenson 2017). Shutting down convection during accretion prevents mixing into the outer layers, confining heavy elements closer to the core. On the other hand, if planetesimals continue to deposit heavy elements as accretion proceeds (the extent to which this occurs is uncertain; e.g., Helled & Lunine 2014), they will not be mixed until after accretion when cooling begins. Depending on the distribution of heavy elements, the inward growth of the convection zone may be suppressed, significantly delaying cooling (e.g., Leconte & Chabrier 2012; Vazan et al. 2016).

In this Letter, we have focused on the thermal contribution to the stratification and assumed a homogeneous composition. It will be interesting to incorporate the thermal stratification in models that compute the composition gradients in the evolution to crossover mass and then runaway accretion phase (e.g., Helled & Lunine 2014; Lozovsky et al. 2017). The continued accretion of planetesimals and the resulting accretion luminosity deposited in the envelope could alter the thermal structure.

We have also assumed here that the accretion rate and shock efficiency $\eta$ are constant during runaway accretion. Further investigations of the radiative transfer associated with the shock are needed to determine how the shock efficiency evolves.

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