Circumplanetary disks around young giant planets: a comparison between core-accretion and disk instability

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ABSTRACT
Circumplanetary disks can be found around forming giant planets, regardless of whether core accretion or gravitational instability built the planet. We carried out state-of-the-art hydrodynamical simulations of the circumplanetary disks for both formation scenarios, using as similar initial conditions as possible to unveil possible intrinsic differences in the circumplanetary disk mass and temperature between the two formation mechanisms.

We found that the circumplanetary disks mass linearly scales with the circumstellar disk mass. Therefore, in an equally massive protoplanetary disk, the circumplanetary disks formed in the disk instability model can be only a factor of eight more massive than their core-accretion counterparts. On the other hand, the bulk circumplanetary disk temperature differs by more than an order of magnitude between the two cases. The subdisks around planets formed by gravitational instability have a characteristic temperature below 100 K, while the core accretion circumplanetary disks are hot, with temperatures even greater than 1000 K when embedded in massive, optically thick protoplanetary disks. We explain how this difference can be understood as the natural result of the different formation mechanisms. We argue that the different temperatures should persist up to the point when a full-fledged gas giant forms via disk instability, hence our result provides a convenient criteria for observations to distinguish between the two main formation scenarios by measuring the bulk temperature in the planet vicinity.

Key words: accretion discs – hydrodynamics – methods: numerical – planets and satellites: formation – planet-disc interactions

1 INTRODUCTION
During the last stage of giant planet formation, a disk forms around the gas-giant which regulates the gas accretion onto the planet and from which the satellites form. These disks are called circumplanetary or subdisks; the latter referring to them being embedded in the circumstellar disk. The two widely accepted planet formation theories, core accretion (Pollack et al. 1996) and gravitational instability (Boss 1997) both predict that circumplanetary disks form around giant planets (e.g. Quillen & Trilling 1998; Canup & Ward 2002; Ward & Canup 2010).

As of yet, there is no observational evidence of a subdisk; therefore, we have to rely on numerical simulations to examine its properties. The observational efforts have just began, e.g., with the Atacama Large Millimeter Array (Pineda et al. 2016 in prep., Perez et al. 2015); therefore, making predictions for such observations from hydrodynamical models are crucial. Furthermore, the characteristics of the circumplanetary disks are also very important for satellite formation theory, because the timescales and the formation mechanism itself are still undetermined (e.g. Canup & Ward 2002; 2006; Mosqueira & Estrada 2003a,b).

In work so far, the masses of subdisks formed via gravitational instability (GI) or core accretion (CA) have been significantly different. The GI smoothed particle hydrodynamical simulations of Shabram & Boley (2013) found very massive subdisks, with 25% of the planetary mass within the circumplanetary disk (CPD). Similarly, Galvagni et al. (2012) and Galvagni & Mayer (2014) recovered 0.5 M_p subdisks. Limitations of these simulations included low resolution and short time evolution. Furthermore, they only fol-
allowed the collapse of an isolated clump extracted from a global disk simulation, and therefore neglected further mass accretion and angular momentum transport from the circumstellar disk. On the other hand, CA simulations always resulted in orders of magnitude lighter CPDs (0.1-1% of the planetary mass). The radiative, 2D models of D’Angelo et al. (2003) found a CPD mass of $10^{-4}M_{\text{Jup}}$ for a Jupiter-mass planet, similar to the isothermal 3D simulations of Gressel et al. (2013). The isothermal 3D simulations of Szulágyi et al. (2014) resulted in a CPD mass of $2 \times 10^{-4}M_{\text{Jup}}$ around a Jupiter-mass planet, while the radiative 3D simulations of Szulágyi (2015) found $1.5 \times 10^{-3}M_{\text{Jup}}$ for the same massive gas-giant. In conclusion, simulations so far found that the GI formed CPDs more than two orders of magnitude more massive than CA formed subdisks.

Regarding the temperature of the CPD, the CA and the GI simulations predict an order of magnitude difference as well. All non-isothermal core-accretion investigations agreed that the peak temperature in the inner subdisk is very high. The temperatures, of course, depend on the resolution of the simulations and on the treatment of the planetary; therefore, it is not surprising that different investigations measured somewhat different peak temperatures. For a Jupiter-mass planet, Ayliffe & Bate (2009b) argued for $T = 1600$ K at the planet surface (defined at 0.02 $R_{\text{Hill}}$). They found much a higher value, $T = 4500K$, with a realistic (i.e. smaller) planetary radius. Of course, the temperature also depends on the viscosity — through viscous heating — as was pointed out by D’Angelo et al. (2003). Their 2D radiative simulation gave a maximum of $T = 1500$ K with their highest viscosity case ($10^{3.6} \text{cm}^2 \text{ s}^{-1}$) for a Jupiter-mass planet. The magnetohydrodynamic simulations of Gressel et al. (2013) studied somewhat lower mass cores, growing the planet from 100 $M_{\text{Earth}}$ to 150 $M_{\text{Earth}}$, but already at these low-mass cores the temperature peaked over 1500-2000 K. Similarly, in the work of Papaloizou & Nelson (2005), the characteristic temperatures in the CPD were 1000-2000 K. The highest resolution CA simulation of Szulágyi et al. (2016a) found a maximal temperature of 13000 K when the resolution was around $110000 \text{ km}$, i.e. 80% of a Jupiter-diameter. This temperature, therefore, refers to a layer below the planetary surface of a young, puffed up protoplanet. All the above mentioned non-isothermal CA works agreed that the temperature profile of the subdisk is very steep: from the maximal temperatures near the planet surface it quickly declines towards the edge of the subdisk. On the other hand, the GI studies found significantly lower temperatures in the planet’s vicinity. Shabram & Boley (2013) had a peak temperature of only 40 K, while Galvagni et al. (2012) obtained temperatures in the range 50-100 K in the rotationally supported envelope of the protoplanetary clump which they identified as the CPD. The latter work was able to follow the clump collapse because of two orders of magnitude higher resolution (a few Jupiter radii) and showed that the inner core of the clump heats up rapidly to temperatures of higher than 1000 K, at which point dissociation of molecular hydrogen begins at the center. In the meantime, the circumplanetary gas remained cold (<100 K). These simulations were among the first ones to show that, in GI, very soon after the collapse a clear dichotomy arises in all physical properties between an inner dense, slowly rotating core and an outer extended circumplanetary envelope or disk.

Another important difference between the CA and GI models is the mass of the circumstellar disk. The GI simulations obviously require very massive protoplanetary disks (usually $\sim 0.1-0.5 M_{\text{sol}}$) where gravitational instability can occur. In contrast, core accretion simulations use very light circumstellar disks, close to the Minimum Mass Solar Nebula estimate of $\sim 0.01 M_{\text{sol}}$.

The size of the protoplanet is also among the leading differences between the two formation models. In CA, the CPD formation is studied assuming that a full-fledged giant planet has already formed; therefore, approximately a Jupiter radius encloses a mass on the order of Jupiter mass. On the other hand, in the disk instability the CPD forms while the clump begins to collapse, when it has a radius as large as 2-5 AU (Shabram & Boley 2013, Galvagni et al. 2012, Galvagni & Mayer 2013). This means that the gravitational potential well is much deeper in the CA simulations relative to the GI ones. As a consequence, in the former case, the accreting gas can release significantly more energy into heat compared to the second case. This can be understood due to the fact that the accretional luminosity scales inversely proportional to the accretion radius. However, this accretion radius is 1000 times larger at the onset of clump collapse than in the CA model.

An additional potentially important difference between the non-isothermal simulations of the two formation scenarios is how the thermal effects are included. The flux limited diffusion approximation (Kley 1999, Commerçon et al. 2011) is used in a number of works on CA formed subdisks (e.g. Ayliffe & Bate 2009a, Szulágyi et al. 2011a). This method includes both radiative cooling and the heating of photons produced by the accretion luminosity. In contrast, most published GI studies Shabram & Boley (2013), Galvagni et al. (2012), Galvagni & Mayer (2014) include a radiative cooling model designed to roughly match the radiative losses in flux-limited diffusion simulations but which neglects radiative heating via photons produced by highly compressional flows (e.g. shocks) and the effects of radiation pressure (see e.g. Boley et al. 2010, Rogers & Wadsley 2011). Some works on disk instability include flux-limited diffusion approximation, but with very low resolution (Mayer et al. 2007, Rogers & Wadsley 2011, Mayer et al. 2016).

The 1-2 orders of magnitude difference in mass and temperature would predict that observationally, the CA and GI formed subdisks could be distinguished, even if the observations could only set upper limits on the CPD mass. However, these differences might come from the fact that the two sets of simulations are significantly different in the initial parameters. Motivated by these key differences, for the first time we have run simulations with very similar initial parameters (i.e. comparably massive circumstellar disk, semi-major axis, planetary mass, resolution) to unveil the real differences between GI and CA subdisks. For the GI case we perform the first global 3D radiative simulations with enough resolution to clearly separate the CPD and planetary core, and follow the clump collapse to relatively long timescales in order to study how the subdisk evolves. The CA calculations are also state-of-the-art computations, as they are radiative, 3D global disk simulations with mesh refinement, which makes

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them one of the highest resolution studies done so far on circumplanetary disks. If the GI and CA simulations still give discrepancies in the CPD temperature and mass despite the similar initial parameters, they can provide criteria to distinguish subdisks around CA and GI formed planets observationally.

2 METHODS

We use two different numerical methods to study CPDs in core-accretion and disk instability models because the nature of the two problems is different. We used a finite-volume code that has excellent shock capturing capabilities to study core accretion, and a Lagrangian code, which captures well the global disk dynamics and includes self-gravity, to study disk instability.

2.1 Core Accretion Simulations

We performed grid-based, radiative, three-dimensional, hydrodynamic simulations with the JUPITER code (Szulágyi et al. 2014; Szulágyi 2015; Szulágyi et al. 2016a; de Val-Borro et al. 2006; Benítez-Llambay et al. 2015), developed by F. Masset and J. Szulágyi. The code has nested meshes and it is based on a higher order Godunov scheme. The nested mesh technique allows having an entire circumstellar disk while zooming into the planet vicinity with higher resolution.

The radiative module includes a two-temperature approach for the Flux-Limited Diffusion Approximation (e.g. Commerçon et al. 2011). Therefore, the heating comes from adiabatic compression and viscous heating, while the cooling is through adiabatic expansion and radiation (grey-approximation). We used the gas and dust opacities of Bell & Lin (1994); therefore, despite the one-fluid (gas) simulation, the dust contribution to the temperature is taken into account. The dust-to-gas ratio was chosen to be 0.001, i.e., ten times less than the interstellar medium value. This was motivated by the fact that at this evolutionary stage of planet formation, most of the circumstellar disk dust has already been aggregated into larger grains and planetesimals, lowering the opacity of the disk (e.g. Ormel et al. 2009, 2011). The mean molecular weight was set to 2.3, which is the solar mixture value. The equation-of-state is ideal gas, \( P = (\gamma - 1)\epsilon \), where the adiabatic index (\( \gamma \)) is 1.43, \( P \) is the pressure, and \( \epsilon \) is the internal energy. We applied a low, constant kinematic viscosity of \( 10^{-7}a_p^2\Omega_p \), where \( a_p \) is the semi-major axis of the planet and \( \Omega_p \) is the orbital frequency of the planet. The self-gravity of the gas is not included in these simulations.

Our simulations contain an entire circumstellar disk in the spherical coordinate system (azimuth, radius, colatitude) centered on the one Solar-mass star. The main parameters of the simulations are in Table 1. The initial surface density profile of the circumstellar disk was flat, with zero inclination. During the first 150 orbits we run the disk simulation without any planet in it, in order to reach initial thermal equilibrium of the disk. Then, we introduce the 10 Jupiter-mass planet through a mass-taper function, building it up continuously over 50 orbits. After this, the planet mass is kept constant throughout the simulation. The results are obtained after steady state has been reached (175 orbits after the initial thermal equilibrium and 125 orbits after the planet was fully formed).

The nested meshes were introduced one after the other, until steady state has been reached. In these computationally expensive simulations, we have used four levels of refinement of the base mesh that contains the circumstellar disk. The refined patches include the planet vicinity, and with each level they double the resolution. On the finest level, the cell-diameter was, 0.000576854 code units, which equals to 0.00299964 AU in the simulations where the planet was at 5.2 AU, and 0.0288427 AU when the planet was placed at 50 AU.

To avoid the singularity of the gravitational potential, we used the traditional epsilon-smoothing technique, where the gravitational potential is shallower within an \( \epsilon \) distance from the planet:

\[
U_p = -\frac{GM_p}{\sqrt{x_d^2 + y_d^2 + z_d^2 + \epsilon^2}} \tag{1}
\]

where \( x_d = x - x_p \), \( y_d = y - y_p \), and \( z_d = z - z_p \) are the distances from the planet in Cartesian coordinates, with \( \epsilon \) smoothing length equal to 0.00337907 code units on the finest level, i.e. 6 cell-diameters.

More details of the JUPITER code, the simulation parameters, and the implementation can be found in Szulágyi et al. (2016a) and where similar radiative simulations were carried out on Jupiter-mass planets in low mass circumstellar disks.

2.2 Gravitational Instability Simulations

In this paper we also employ a new 3D global disk smooth particle hydrodynamic (SPH) simulation with unprecedented resolution, which is part of a new simulation suite to be presented in a forthcoming paper (Mayer & Quinn, in preparation). This is the first simulation that achieves a resolution of 0.01 AU in a 200 AU disk, comparable to the resolution of individual clump collapse local simulations (Galvagni et al. 2012). It employs as many as 42 million SPH particles. We note that the resolution is comparable to that of the core-accretion simulations described in the previous section for the runs with the planet at large distances (52 AU), which is also the configuration to be compared with the disk instability simulations.

The protoplanetary disk has a mass of 0.6M\(_\odot\) and the central star is 1.35M\(_\odot\), similar to the host star in the HR8799 system, the prototypical system with massive gas giants on wide orbits (\( R > 30 \) AU) that could have been formed via disk instability. The disk temperature profile is set up in hydrostatic equilibrium using a highly accurate iterative procedure that takes into account full force balance and stellar irradiation at time \( t = 0 \), including disk self-gravity (Mayer et al. 2016).
al. 2016 | Rogers & Wadsley 2011). The surface density profile is a power law with an exponent close to \( -1 \) in the region where fragmentation is expected to happen \( (R \sim 30 \text{ to } 100 \text{ AU}) \) due to shorter cooling times and low Toomre Q parameter \( (\text{the minimum Toomre Q drops initially below } 1.4 \text{ at } R = 60 \text{ AU}) \), and has two exponential truncations at the inner and outer edge of the disk, which are set at 5 AU and 200 AU, respectively. The central star is treated as a sink particle \( \text{[Rogers & Wadsley 2011]} \), with a sink radius equal to 4 AU.

The GI simulation presented in this paper was carried out with the new ChaNGa Tree+SPH code, which employs a CHARM++ parallel programming environment to enable dynamic load balancing on large supercomputers \( \text{[Jetley et al. 2008; Menon et al. 2015]} \). ChaNGa inherits its basic SPH implementation from the GASOLINE and GASOLINE2 codes \( \text{[Wadsley et al. 2004; Keller et al. 2014; Tamburello et al. 2015]} \), widely used in radiation hydrodynamic simulations of 3D self-gravitating disks \( \text{[e.g. Mayer et al. 2002; 2007; 2016; Rogers & Wadsley 2011]} \). As in GASOLINE2, ChaNGa employs a modern SPH implementation which uses a geometric weighting of the density estimate \( \text{[Keller et al. 2014; Governato et al. 2015]} \) resulting in a formulation of the pressure force analogous to that presented in Hopkins (2013) and Ritchie & Thomas (2001). Combined with a turbulent diffusion term in both the momentum and internal energy equation — whose formulation is described in Shen et al. (2010) — and the adoption of an optional Wendland C4 kernel, it avoids artificial surface tension, resolving the mixing of different fluid phases and physical hydrodynamic instabilities at contact discontinuities.

These new features have been shown to bring SPH in good agreement with finite volume grid-based codes with accurate Riemann solvers \( \text{(Hopkins 2014)} \) in modeling the properties of the flow, while keeping the advantage of a Lagrangian code in modeling disk dynamics. It provides perfect angular momentum conservation and no advection errors, which allows the capturing of processes such as ablation of clumps by ram pressure, that have never been reported before in either SPH or (fixed) grid simulations \( \text{(Mayer & Quinn, in preparation)} \).

Also as in GASOLINE, ChaNGa uses a Monaghan viscosity with \( \alpha = 1 \) and \( \beta = 2 \), and a switch to limit the viscosity in purely rotational flows \( \text{[Balsara 1995]} \). The radiative cooling is based on local gas properties. For this, we write the energy loss per time per volume as:

\[
\Lambda = (36\pi)^{1/3} s \frac{T^4 - T_{\text{min}}^4}{T_{\text{min}}} \frac{\tau}{\tau^2 + 1} \tag{2}
\]

where \( \tau \) represents the optical depth across a resolution element, \( T_{\text{min}} \) is the minimum gas background temperature \( (10 \text{ K}) \), \( s = (m/\rho)^{1/3} \) and \( \sigma \) is the Stefan-Boltzmann constant. While equation \( \text{(2)} \) is only approximate, it allows us to capture the general behavior of radiative cooling while making the computation much faster than with full-fledged radiative transfer. Cooling is most efficient at an optical depth \( \tau \sim 1 \), and the two asymptotic limits for large and small \( \tau \) recover the dependence of cooling rate on optical depth in the optically thin and optically thick limits. This cooling prescription compares reasonably with flux-limited diffusion calculations, as described in Boley (2009) and Boley et al. (2010). As we do not solve the radiation hydrodynamics equation in the diffusion limit, the accretional luminosity of contracting clumps is not included. However, the compressional heating — generated by PdV work — and the shock heating is taken into account.

For comparison, and in order to investigate the effect of radiation physics, we also use another version of this simulation that has 40 times lower mass resolution \( \text{(gravitational softening } 0.16 \text{ AU} \) \) but includes mono-frequency radiative transfer \( \text{[Mayer et al. 2016]} \). This simulation of Mayer et al. (2016) was carried out with the GASOLINE code using the implicit method for flux-limited diffusion with photospheric cooling described in Rogers & Wadsley (2011), which has been shown to reproduce expected radiative losses at the disk boundary correctly, a significant improvement over previous methods of disk edge detection in SPH \( \text{(e.g. Mayer et al. 2007)} \).

In order to compute optical depths we used tabulated Rosseland mean and Planck opacities from D’Alessio et al. (1997) and D’Alessio et al. (2001) for the gas at solar metallicity \( \text{(assuming a dust-to-gas ratio } = 0.01 \) \). We included also a variable adiabatic index that takes into account the variation of the ortho/para ratio of molecular hydrogen as a function of temperature, which is important to capture the thermodynamics across spiral shocks in self-gravitating unstable disks \( \text{[Podolak et al. 2011]} \). In order to speed-up further the simulations during the computationally intensive phase of clump collapse we shut-off cooling in the clump core when it has collapsed to about 6 orders of magnitude higher density than the background. This essentially slows down the collapse in the inner region compared to Galagni et al. (2012) but becomes necessary for computational reasons in order to evolve the disk for longer. We have tested that it has no effect on the circumplanetary disk by running a parallel computation with no cooling shut-off.

## 3 RESULTS

### 3.1 The formation of the circumplanetary disk

In the core accretion simulations, the CPD forms quickly while the 10 Jupiter-mass planet is built up through the mass-tapering function \( \text{(see right-hand panel of Figure 1)} \). Because it is not possible to follow the entire core-accretion via hydrodynamic simulations, this initial fast planet augmentation is necessary in order to study the late stage of planet formation when a circumplanetary disk forms around the gas-giant. During this phase, the subdisk is still fed by a vertical gas influx from the circumstellar disk such as described in Szulágyi et al. (2014). The planet has opened a partial, eccentric gap in the gas of the protoplanetary disk \( \text{(see left-hand panel of Fig. 1)} \).

In the GI simulation the disk fragments into multiple clumps in the region at 60 – 80 AU from the center after about 500 years, namely about one disk rotation. While a detailed description of this and other similar simulations is deferred to a forthcoming paper \( \text{(Mayer & Quinn, in preparation)} \) here we focus on the formation of the circumplanetary disks. The clumps form with a wide range of masses, ranging between 2 and 20 Jupiter masses. Some condense out of spiral arms in relative isolation while others appear to be triggered by a strong perturbation from other clumps forming earlier \( \text{(see also Armitage & Hansen 1999; and Meru} \)
The first 2-3 disk rotations after the onset of fragmentation mark a highly chaotic phase in which protoplanetary clumps interact vigorously among themselves and with the surrounding disk. The clumps lose mass via mutual tidal interactions and due to inward orbital migration, which in some cases appears to occur quickly, on the orbital timescale (Malik et al. 2015), and simultaneously accrete mass from the disk. In all cases a CPD appears at the same time as the clump formation, as the subdisk results from the higher angular momentum material accreted from the protoplanetary disk that can reach centrifugal equilibrium around the denser core that first collapses from the spiral arm (Boley et al. 2010). The clear dichotomy between an inner dense core and an outer much more diffuse envelope, where rotation is dynamically important, can be seen on Figure 2. Here we show the normalized angular momentum (i.e. rotational velocity divided by the local Keplerian velocity) profile for the 10 Jupiter-mass clump soon after fragmentation. Clearly, the region between ∼2-6 AU has the largest rotation beyond the planet, this is what we will define as circumplanetary disk in the next Section.

Figure 3 shows two snapshots of the GI simulation in the early and late stage of the simulation, respectively. The second snapshot shows only 4 clumps remaining among those initially formed. Indeed, merger, inward migration and tidal mass loss are responsible for disrupting about more than half of the initially formed clumps. After 10^3 years, the protoplanetary disk settles into a more quiet phase as its Toomre Q has risen enough to make it relatively stable. At this stage we are left with a massive gas giant of ∼10 Jupiter masses, an larger one on the order of 20 Jupiter masses, and two even more massive objects that are clearly in the brown dwarf regime. These clumps are on eccentric orbits and have reached very high central densities at which dissociation would have already begun if included (see Section 4). Indeed, the densities are comparable to those in Galvagni et al. (2012) before the onset of dissociation, which is not included here and would not be reached anyway since we shut-off the cooling in the core well before it reaches that density. Following dissociation, the core would collapse dynamically in timescales of years to the density of Jupiter (Bodenheimer 1989; Helled et al. 2006). This “second collapse” phase would occur below our resolution limit, hence it cannot be followed here. It is therefore likely that these protoplanets and proto-brown dwarfs will survive indefinitely even if they migrate to less than an AU from the star, although most of the CPD could be stripped in that case (see Discussion Section).

The subdisk around the GI formed 10 M_{Jup} protoplanet has grown in mass during the interactions of the clumps, but the ratio between CPD mass and protoplanet mass has remained roughly constant, only increasing slightly (see Sect. 3.5). We will focus our analysis, in the rest of the paper, on the lowest mass object, the gas giant with mass around 10 Jupiter-masses; however we also have studied the other...
clumps to confirm that the results presented here on the properties of the CPD are general.

3.2 Defining the CPD boundaries

To obtain the mass of the circumplanetary disk, we first need to define its boundaries. There are three main ways to define the boundary, namely:

(i) draw streamlines and account for the area where the flow is bound to the planet (i.e. orbiting around it)
(ii) compute the eccentricity of the orbit of a fluid-element at various radii from the planet, then use the circular orbits to define the boundaries; however, in case of massive planets — such as in this work — the CPD can become eccentric, so this method would not be suitable
(iii) calculating the normalized angular momentum around the planet, meaning the z-component of the angular momentum normalized by the local Keplerian velocity at a given radius; then setting a minimum value — i.e. how sub-Keplerian the gas is in the CPD — sets the boundaries.

The work of Szulágyi et al. (2014) showed that the first and third methods lead to roughly the same, $0.5 \, R_{\text{Hill}}$, CPD radius in the case of a 1 $M_J$ planet at 5.2 AU. In this work, however, we define the CPD boundaries via the normalized angular momentum, because comparing the GI and CA simulations with this quantity is particularly useful. We decided on a 45% minimum Keplerian rotation to define the boundaries of the subdisks. Therefore the mass integral within this region, —where the normalized angular momentum is larger than 0.45 — in all the different simulations can lead to a valid comparison of the CPD-masses. Furthermore, we checked the streamline method, and we get roughly the same radius for the CPD as that from the > 0.45 normalized angular momentum value.

Because the definition of the CPD borders is still arbitrary, we also compared the mass of the entire Hill-spheres. The CPD is definitely a subset of the Hill-sphere, and the Hill-sphere is easily definable with $R_{\text{Hill}} = a_p (M_p/M_*)^{1/3}$; therefore, the comparison of the Hill-sphere masses can eliminate any possible uncertainty of the CPD mass comparisons due to the arbitrary subdisk borders.

3.3 Comparing the Density profiles and Masses

As mentioned in the previous section, when calculating the masses of the CPD, we integrated the mass where the rotation of the gas is at least 45% Keplerian. From the CA simulations — since all planets were 10 $M_{\text{Jup}}$ — we compared the CPD masses with the circumstellar disk masses (see Fig. 4). The error bars were calculated as the standard deviation of 10 outputs of the simulation over one orbit of the planet. Surprisingly, even in the case of radiative simulations the CPD mass seems to (nearly) scale linearly with the circumstellar disk mass, with the relation

$$M_{\text{CPD}} = M_{\text{CSD}} \cdot (2.26 \pm 0.12) \cdot 10^{-3} + (6.49 \pm 2.37) \cdot 10^{-2}$$ (3)

This linear relationship is very important especially for observations aiming to detect the CPD, because it means that the mass of the subdisk is not necessarily related to the mass of the planet, rather, more massive circumstellar disks will have more massive circumplanetary disks. Therefore, observations should not target very massive gas-giants to detect the subdisk, but instead target massive circumstellar disks where the planet has opened a gap (and therefore the gap region is optically thin).

We also compared the entire Hill-sphere masses with the circumstellar disk mass (Fig. 4). The relationship is again linear:

$$M_{\text{Hill}} = M_{\text{CSD}} \cdot (4.57 \pm 0.60) \cdot 10^{-3} - 0.37(\pm 0.24)$$ (4)

The Hill sphere to CPD mass ratios scale from 1.1 to 1.7 for the CA simulations, and, more massive circumstellar disks have larger mass ratios.

Because the CPD masses scale with the circumstellar disk mass, in our 0.6 $M_{\text{solar}}$ circumstellar disk the subdisk was 1.2 $M_{\text{Jup}}$, giving a CPD-to-planet mass ratio of 12%. This is a significantly higher ratio than found so far in CA simulations, $10^{-1} - 10^{-3} M_{\text{planet}}$ (Gressel et al. 2013; Ayliffe & Bate 2009b; Szulágyi et al. 2014, 2016a). Now it is under-
standable that the reason for the discrepancy is that those works all used very light circumstellar disks (∼10\(M_{\text{Jup}}\)), so the CPD is correspondingly less massive. So far, the GI subdisk simulations predict 25% \(M_{\text{planet}}\) \cite{Shabram2013} and 50% \(M_{\text{planet}}\) \cite{Galvagni2012}. Comparing with these values from GI simulations, the CPD-to-planet mass ratios in CA simulations are lower, not by several orders of magnitude, but only by a factor of eight. Therefore, it cannot be said that GI formed CPDs are definitely more massive; it will depend on the circumstellar disk mass. Thus, observationally, the CA and GI formation mechanisms cannot be distinguished with confidence solely from the observed CPD masses.

The subdisk masses in our GI simulations reach values even higher than the aforementioned 25-50% of the planetary mass. Applying our normalized angular momentum threshold of 0.45 we find that soon after the clump forms the CPD mass is about 6 \(M_{\text{Jupiter}}\) compared to 10 \(M_{\text{Jupiter}}\) for the protoplanetary core inside it. At the latest time (corresponding to the snapshot on the right of Figure \[5\]), the subdisk grows to about 10 Jupiter-masses while the protoplanetary core, which has continued to collapse, has grown only to about 13 \(M_{\text{Jupiter}}\). Hence, the CPD-to-planet ratio is roughly 60% of the protoplanet mass at the beginning, in substantial agreement with the results of \cite{Galvagni2012}, while at later times it becomes comparable to the protoplanet mass. We note that at late times the clump has acquired a very eccentric orbit, moving out to \(R > 150\) AU and gathering high angular momentum gas from the outer fringes of the disk. Accretion along this outgoing orbit might explain the increasing CPD mass with time relative to previous work. (We note, in particular, that the collapsing clumps studied in \cite{Galvagni2012} were isolated hence the interplay between accretion and orbital evolution was missing by construction.)

We also compared the midplane density profiles of the CA and the GI simulations, see Fig.\[5\]. The CA-2 and CA-3 calculations predict larger volume densities in the midplane than the gravitational instability calculations, while the CA-1 simulations gives the lowest density in the midplane. This is due to the fact that the core accretion simulations are more compact: the planet is a point-mass, and the circumplanetary disk is not as extended as in the GI case. In the GI simulations, the planet is not a point mass, but an extended clump which is still collapsing. Fig.\[5\] is plotted with respect the Hill-radius, but the Hill-spheres are significantly different in physical size in the various simulations. This is the reason why the GI simulation has lower or comparable volume density in the midplane, but an overall more massive Hill-sphere, than in the CA simulations.

As we discuss later in the Discussion section, with increased resolution, and with the inclusion of molecular dissociation in the GI simulations, the core is expected to collapse into a fully fledged planet of a few Jupiter radii in < 10^7 years \cite{Helled2014}, as hinted by the isolated collapse simulations of \cite{Galvagni2012}. However, what fraction of the mass would actually collapse to this final state depends on the angular momentum profile at small radii. In \cite{Galvagni2012} the angular momentum transport from the core to the CPD was occurring due to non-axisymmetric instabilities, which appear not to be captured yet in our global simulations as we limit the cooling above a certain density. Resolving angular momentum transport processes is important in order to answer the following question; when exactly will the protoplanetary core become compact enough to be similar to the planet configuration in the CA simulations? When this happens, one would expect the CPD to evolve towards a state similar to the subdisk in the CA simulations. However, there is one aspect that will prevent the two scenarios from converging, namely the fact that the clump in the GI simulations has a significantly higher angular momentum budget. In the late stage, the total angular momentum of the subdisk in the GI simulation is about an order of magnitude higher than in the CA-1 simulation. Nevertheless, the specific angular momentum is comparable in the two cases, indicating that they are both built from material accreted from the outer circumstellar disk. The much larger CPD mass in the GI simulation (11\(M_{\text{Jup}}\) as opposed to 0.5\(M_{\text{Jup}}\) in the CA-1 computation) creates a major division for the subsequent dynamical evolution. In the GI case, the protoplanetary core and the CPD will continue to collapse together, while in the CA, the subdisk will accrete onto an already compact planet.

### 3.4 Comparing the Temperature Profiles

We compared the midplane temperature profiles of the three core-accretion simulations and the gravitational instability calculations inside the Hill-sphere (Fig.\[5\]). We found more than an order of magnitude difference in the bulk temperature between the core-accretion and the gravitational instability predictions. The latter predicts a characteristic temperature of \(\sim 50\) K in the circumplanetary disk (between \(\sim 0.1\) and 0.3 Hill-radii), while the core-accretion simulation with the planet at 50 AU predicts 800-1000K inside the circumplanetary disk defined in Sect. 3.2.

If we compare the various core-accretion simulations with each other, we see that the Hill-sphere gas has a higher
bulk temperature when the planet is at 5.2 AU in contrast with the 50 AU simulation. However, the difference does not come from the different semi-major axes, partially because we did not use stellar irradiation in these calculations. Instead, the difference in temperature is due to different circumstellar disk masses. In all the calculations we used a dust-to-gas ratio of 0.001; therefore, the amount of the integrated dust in the disk is also higher when the circumstellar disk mass is higher. Dust is the main heating source in protoplanetary disks, because the more dust we have, the greater the optical depth of the disk; hence, the cooling is less efficient. Even though our temperature of the CPD coincides with the drop in opacity at the dust sublimation temperature assumed in the Bell & Lin (1994) opacity table, the CPD is optically thick even across this opacity drop due to dust sublimation and the high density. If we compare the temperature profiles of this work and Szulágyi et al. (2016a), where the Jupiter-mass planet is embedded in a ~10 M\textsubscript{Jupiter} circumstellar disk, we see that the temperatures are significantly lower there.

When comparing the temperatures of two different simulations, especially with two different methodologies (here grid based and smoothed particle hydrodynamic computations), it is important to understand how the temperature is affected by the numerics. As we described in Sect. 2, the core-accretion simulations were carried out with the flux limited diffusion approximation, while the GI calculations were done with a phenomenological cooling law that was calibrated to flux limited diffusion results with the same code. Another important factor for the temperature calculations is the resolution. Our hydrodynamic resolutions are comparable, the GI resolution being 10^{-2} AU while the core-accretion is 3 x 10^{-2} AU for the planet at 50AU (simulation CA-1) and 3 x 10^{-3} AU for the planets at 5.2 AU. The gravitational softening in the GI case was 0.01 AU, while it was 0.17 AU for the CA-1 simulation and 0.017 AU for CA-2 and CA-3. Therefore, the comparable resolutions and gravitational softenings provide valid comparisons for the temperature.

In order to check whether the lack of the flux limited diffusion approximation in the GI simulation has an effect on the temperature, we did a comparison with a similar simulation with the flux limited diffusion approximation included (Mayer et al. 2016) that was carried out with a similar SPH code (see Figure 7). The clump from Mayer et al. (2016) had a mass of 8 M\textsubscript{Jupiter}, so similar to our 10 M\textsubscript{Jupiter} protoplanet. Due to the inclusion of the flux limited diffusion approximation in Mayer et al. (2016), the resolution is lower, and the simulation timespan is shorter than in this work. Nevertheless, as it can be seen, the comparison result is re-assuring as the temperature in the outer region corresponding to the CPD is below 100 K, significantly lower than the flux limited diffusion core accretion simulations.

The reason for the temperature difference between the CA and GI simulations is twofold. First, the optical depth is, of course, playing a large role in determining the cooling rate. Because the CA-2 and CA-3 simulations have larger densities close to the planet than the GI calculation (see Sect. 3.3), the gas is more optically thick, and it cools less efficiently than in the GI case. In the GI case, optical depths are of order unity in the CPD region (but increasing to > 1000 in the core), since they reflect the conditions necessary in the disk for gas to be able to fragment and form a clump, i.e. the cooling time has to be a few times the local orbital time (Gammie 2001, Rafikov 2003, Clarke & Lodato 2009). Secondly, the profile of the gravitational potential well — i.e. the size of the protoplanet — is also significantly affecting the temperature. In the GI simulations the protoplanet has initially a size of few AU before it begins to collapse. On the other hand, in the CA calculations, an entire 10 Jupiter-mass planet is compressed into a point mass with a gravitational softening of 0.17 AU or 0.017 AU, for planets at 50 AU and 5.2 AU respectively. This means that the gravitational potential well is narrower and deeper in this case than in the GI simulations. Therefore, the gas can...
Circumplanetary disk comparison between core-accretion and disk instability

Figure 7. Comparison of the clump temperature profiles with a flux limited diffusion simulation from Mayer et al. (2016) (green) and this work (red) with local cooling. Clearly, the full radiative transfer with flux limited diffusion also gives very low clump and subdisk temperatures, similar to what was found in this work. Hence, the more than an order of magnitude temperature difference found between our GI and CA simulations is robust.

3.5 Time-evolution of the disk instability simulations

In the case of the gravitational instability simulations, a steady state cannot be reached by the end of the simulations. A clump of a few Jupiter masses is expected to collapse into bona-fide gas giant of about a Jupiter radius in $10^4 - 10^5$ years, depending on the angular momentum, the metal enrichment during the collapse, the mass accretion rate from the disk, and other conditions (Helled et al. 2014). The collapse timescale is generally defined as the time it takes to reach H$_2$ dissociation, which triggers a dynamical collapse. It is numerically very challenging to follow the collapse all the way with hydrodynamic simulations, partially because the more compact the clump, the slower the computation. We managed to follow the GI collapse for almost a hundred CPD dynamical times, thanks to access of one of the fastest supercomputers in the world. Once the inner dense core of the clump contracts to a couple of gravitational softening lengths ($\sim$ 0.02 AU) the collapse is artificially halted in our GI simulation, but this is not an issue for studying the subdisk.

Figure 8 shows the time evolution of the clump’s density in the midplane between 1034 and 2736 years. As the clump collapse to form the planet, the peak density in the center increases, while in the outer parts of the clump the density decreases. Understanding the time evolution of the simulation is important when comparing it with the CA simulations, where steady state has already been reached.

We also show on Fig. 9 how the temperature changes during the collapse of the clump. While the temperature rises in the central parts (i.e. the interior of the protoplanet) by $\sim$ 160 K over 1700 years, the outer parts of the clump, what we call the circumplanetary disk remains roughly at the same temperature ($\sim$ 20 – 60K). This gives us a robust comparison of temperature with the core-accretion simulations.

2 Note that accretion is still ongoing in the CA simulations; therefore, the density does increase in the innermost cells around the planet point-mass.

\[ L_{\text{acc}} = \frac{G M_p \dot{M}_p}{R_p} \]
where the protoplanetary disk mass is higher (at present, or had low masses too. In other planetary systems, however, the circumstellar disks around our gas-giants must have our Sun probably had a rather low mass circumstellar disk, given that the feeding and mass loss balance, and it changes as the subdisk mass is not constant in time, but depends on the subdisk. If the CPD is threaded by a magnetic field, an extended, cold CPD is present for up to 10^5 years, or there is no CPD if it has been lost by tides during migration. In no case do we expect a hot CPD akin to that in the core-accretion case.

In the case of our Solar System, where the giant-planets were most likely formed via core-accretion, the integrated mass of Jupiter’s and Saturn’s satellites makes up 2 × 10^{-4} of the planetary mass. Assuming the interstellar medium value for the dust-to-gas ratio (i.e. 1% dust), this would mean a minimum mass for the CPD of 2% of the masses of our two largest gas-giants. However as Canup & Ward [2002] pointed out, this mass has to be processed during the entire satellite growth timescale, i.e. it does not all have to be present at one given instant of time. The reason is that the CPD is not a closed reservoir of mass, unlike the circumstellar disk. The subdisk is fed by the circumstellar disk, and loses mass through the accretion onto the planet. Therefore, the subdisk mass is not constant in time, but depends on the feeding and mass loss balance, and it changes as the circumstellar disk evolves and the planet grows. Given that our Sun probably had a rather low mass circumstellar disk, the circumplanetary disks around our gas-giants must have had low masses too. In other planetary systems, however, where the protoplanetary disk mass is higher (at present, or at earlier stage), the CPD mass can be also higher and can result in more massive, more extended satellite systems.
which can survive even at orbital radii of ~1 AU at the densities found at the end of our GI simulation. Since massive protoplanets in massive self-gravitating disks can migrate inward on timescales of < 10^5 year, we argue that detection of the original CPDs formed by disk instability is more likely in the early evolutionary phase of the protoplanetary disk, before the Class II stage. Later, a new subdisk might be accreted by the newly formed gas giant, but it will be much more compact than the first population of GI subdisks. These second generation of CPDs probably will have thermodynamic properties analogous to core-accretion subdisks, given that they formed around fully fledged giant planets. If such a second generation exists, then the CPDs between the two formation mechanism will not likely differ much.

5 CONCLUSION

In this paper we compared the main characteristics (mass & temperature) of circumplanetary disks around core accretion and gravitational instability formed gas giants. We used state-of-the-art hydrodynamic simulations with as similar initial parameters as possible to reveal the key differences between the subdisks of the two main planet formation scenarios.

The core accretion simulations were carried out with the JUPITER code, featuring a radiative module with the flux limited diffusion approximation and mesh refinement. The disk instability simulations were performed with the ChaNGa smoothed particle hydrodynamic code, matching the resolution of the grid-based simulations and having a radiative cooling calibrated to flux limited diffusion results. We ran three core accretion and one disk instability simulation with 10 Jupiter-mass planets in massive circumstellar disks (158, 290 and 600 M_{\text{Jup}}). In two core accretion simulations the planets had a semi-major axis of 5.2 AU, the third simulation featured a gas-giant at 50 AU distance from its star. In the GI calculations the semi-major axis was also 50 AU for our chosen, 10 Jupiter-mass protoplanet, although the orbit varied a bit through interactions with other clumps.

We found from the core-accretion simulations that the subdisk mass linearly scales with the circumstellar disk mass, even in these radiative simulations. This means that core accretion CPDs can be nearly as massive as their GI counterparts, if the protoplanetary disk has the same mass. In the 0.6 M_{\text{sol}} circumstellar disks, the CA simulation resulted in a CPD with a mass of 12% M_{\text{Jup}}, while we found a CPD mass of 50%-100% M_{\text{Jup}} in the GI computation. Previous works predicted a 4-5 orders of magnitude mass discrepancy, but we were able to show that was because of their orders of magnitude differences in circumstellar disk masses.

On the other hand, our finding is that the temperature differs by more than an order of magnitude between the GI and CA formed CPDs. According to the simulations, the bulk subdisk temperature is < 100 K in the case of disk instability, and over 800 K for all the CA computations presented in this paper. The reason for this discrepancy lies in the different gravitational potential wells and opacities. Because the protoplanet is a few AU wide extended clump in the GI simulations, while it is a fully formed giant planet with a radius of 0.17 AU (meaning the gravitational potential smoothing length) in the CA-1 simulation, the accreted gas has significantly more energy to release into heat in the latter case than in the former.

The large temperature contrast between CA and GI circumplanetary disks provides a convenient tool for observations on young, embedded planets to distinguish between the two main formation mechanisms.

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