Effects of the Planetary Temperature on the Circumplanetary Disk and on the Gap

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Abstract

Circumplanetary disks (CPDs) regulate the late accretion to the giant planet and serve as the birthplace for satellites. Understanding their characteristics via simulations also helps to prepare for their observations. Here we study disks around 1, 3, 5, and 10 $M_{\text{Jup}}$ planets with 3D global radiative hydrodynamic simulations with sub-planetary peak resolution and various planetary temperatures. We found that as the $1 M_{\text{Jup}}$ planet radiates away its formation heat, the circumplanetary envelope transitions to a disk between $T_p = 6000$ and $4000$ K. In the case of 3–10 $M_{\text{Jup}}$ planets, a disk always forms. The temperature profile of the CPDs is very steep, the inner 1/6th is higher than the silicate condensation temperature, and the entire disk is higher than the water freezing point, making satellite formation impossible in this early stage (<1 Myr). Satellites might form much later and first in the outer parts of the disk, migrating inwards later on. Our disk masses are 1, 7, and $20 \times 10^{-3} M_{\text{Jup}}$ for the 1, 3, 5, and 10 $M_{\text{Jup}}$ gas giants, respectively, and we provide an empirical formula to estimate the subdisk masses based on the planet-and circumstellar disk (CSD) mass. Our finding is that the cooler the planet, the lower the temperature of the subdisk, and the higher the vertical influx velocities. The planetary gap is also both deeper and wider. We also show that the gaps in 2D and 3D are different. The subdisk eccentricity increases with $M_p$ and violently interacts with the CSD, making satellite-formation less likely when $M_p \gtrsim 5 M_{\text{Jup}}$.

Key words: hydrodynamics – methods: numerical – planets and satellites: detection

1. Introduction

During the final planet formation phase, giant planets are surrounded by their own disk, the circumplanetary disks (CPD). We also call these disks subdisks because they exist within the circumstellar disk (CSD). Their importance lies in the fact that they are regulating the late gas accretion to the planet, and they are the birthplace for satellites to form. From a planet formation and satellite formation perspective, we therefore need to understand their characteristics better. With no clear observational evidence of such subdisks until today, we have to rely on hydrodynamics simulations to unveil their properties.

We are just entering an era when the detection of the CPD is possible. Extended thermal emission around embedded, young, forming planets has been detected with direct-imaging observations in a number of sources (e.g., Kraus & Ireland 2012; Brittain et al. 2014; Reggiani et al. 2014; Quanz et al. 2015; Sallum et al. 2015). These extended thermal emissions suggest that these young planets are surrounded by hot gas and dust, most likely in the form of CPDs or CSD-envelopes. Recently, Sallum et al. (2015) detected H$\alpha$ emission from one of the planetary candidates around LkCa15, which accretion tracer can either arise from the planet or its CPD if it exists (Szulágyi & Mordasini 2016). Furthermore, in the near future it will be also possible to detect the dust emission of the subdisk with the Atacama Large Millimeter Array (J. Pineda et al. 2017, in preparation, J. Szulágyi et al. 2017, in preparation) or the kinematic imprints of this disk (Perez et al. 2015). In order to prepare for future observations, we need models to predict the basic characteristics—such as mass, temperature, and kinematic properties—of the CPDs. This is also essential for choosing the correct method to detect these subdisks, e.g., via direct imaging, dust emission observations, or line broadening of certain spectral lines.

So far, hydrodynamic studies of subdisks reported quite different characteristics. Regarding the subdisk mass, disk instability simulations of Shabram & Boley (2013) and Galvagni et al. (2012) found very massive CPDs of $\sim 0.25–1.0 M_{\text{planet}}$. On the other hand, all core-accretion works measured masses of around $10^{-3}$–$10^{-4} M_{\text{planet}}$ (Gressel et al. 2013; Szulágyi et al. 2014, 2016a). Szulágyi & Mayer (2016) showed that this discrepancy originates from the significantly different CSD masses in the two formation scenarios. Disk instability requires a very massive CSD ($>0.1 M_{\odot}$), while core-accretion simulations usually work with at least ten times lighter protoplanetary disks. According to Szulágyi & Mayer (2016), the CPDs around planets that formed through core-accretion can be almost as massive as planets formed through disk instability if the CSDs have a similar mass.

Temperature-wise, subdisks formed through core-accretion are an order of magnitude hotter (D’Angelo et al. 2003; Ayliffe & Bate 2009b; Gressel et al. 2013; Szulágyi et al. 2016a) than their counterparts that formed through gravitational instability (Galvagni et al. 2012; Shabram & Boley 2013; Szulágyi & Mayer 2016). For a Jupiter-mass planet, Ayliffe & Bate (2009b) found a 4500 K peak temperature in the CPD when they assumed realistic planetary radius. When they defined the surface of the planet farther out, at 0.02 $R_{\text{Hill}}$, the inner CPD temperature was only 1600 K. Szulágyi et al. (2016a) found a peak temperature higher than 13,000 K for a Jupiter-mass planet with a sub-planet resolution of 80% of the Jupiter diameter. This highlights that the resolution, i.e., the distance to the planetary surface and the peakiness of the gravitational potential well of the planet, greatly matters for the temperature in the vicinity of the planet. Other factors, such as viscosity (D’Angelo et al. 2003) and opacity (Papaloizou & Nelson 2005; D’Angelo et al. 2014), are also playing a role in affecting the heat budget of the subdisk. D’Angelo et al. (2003) showed that higher viscosity means higher temperatures in the CPD as a result of larger shear-stress by viscous forces. The
magnetohydrodynamics simulations of Gressel et al. (2013) studied planets with slightly lower mass, growing them from 100 $M_{\text{Earth}}$ to 150 $M_{\text{Earth}}$ and these low-mass cores already resulted in peak temperatures higher than 1500–2000 K in the subdisk. Similarly, the characteristic temperatures in the CPD were 1000–2000 K in the work of Papaloizou & Nelson (2005) at various dust-to-gas ratios (1% and lower). The peak temperatures do not represent the bulk temperature of the subdisk, however. The temperature profile sharply decreases with the distance from the planet (D’Angelo et al. 2003, 2014; Papaloizou & Nelson 2005; Ayliffe & Bate 2009a, 2009b; Szulágyi et al. 2016a).

With higher planetary mass ($\gtrsim 3 M_{\text{Jup}}$), the gaps become more eccentric, therefore the CPD is also more elongated (e.g., Lubow et al. 1999; Kley 1999; Kley & Dirksen 2006; Lubow & D’Angelo 2006). As Kley & Dirksen (2006) showed, in the $\gtrsim 5 M_{\text{Jup}}$ cases the CSD can regularly engulf the subdisk, creating accretional bursts to the planet. CPDs around these massive planets are particular interesting from an observational point of view, because they are probably more massive and more luminous than their counterparts around Jupiter-mass planets or below (e.g., Zhu 2015; Szulágyi & Mordasini 2016).

From the temperature of CPDs, we can infer when and where satellite formation can occur inside these disks. First of all, the temperature should be lower than the dust (silicate) sublimation point ($\sim 1500$ K) in order to have any hope of forming satellites. Second, from the water ice content of Galilean satellites it is suggested that they had to form in a subdisk at lower than the water freezing point (e.g., Canup & Ward 2002). At first glance, this seems to disprove the core-accretion-formed CPD theory, as the planet radiates away, its formation heat and the CSD gas content is dissipating, presumably the gas-giant vicinity also cools off, eventually reaching a low enough temperature for satellite formation to occur. The timescale of this is still unknown (Canup & Ward 2002, 2006; Mosquera & Estrada 2003a, 2003b; Estrada et al. 2009) and certainly depends on a number of factors, such as the semimajor axis, the opacity of the gas and dust, and the temperature and cooling rate of the planet. Motivated by this and the observational efforts made for the CPDs, in this paper we study how the planetary temperature affects the circumplanetary gas, namely its temperature, mass, and kinematic properties. With a suite of sub-planet resolution simulations with decreasing planetary temperatures for a planet of 1 Jupiter mass, we study how these disk properties change. In the different calculations, we set the maximum planet temperature to 10,000, 8000, 6000, 4000, 2000, and 1000 K according to planet interior and evolution studies (C. Mordasini et al. 2017, in preparation, Guillot et al. 1995). This temperature sequence can also be understood as an evolutionary ordering as the planet cools off, the lowest temperatures representing ages around 1–2 Myr according to C. Mordasini et al. (2017, in preparation) and Guillot et al. (1995). We also carried out simulations for 3, 5, and 10 $M_{\text{Jup}}$ planets with and without a temperature cap. Because the simulations are computationally very expensive, we could not follow a temperature sequence as in the case of the 1 $M_{\text{Jup}}$ planet, but we simulated two cases: a varying temperature ($\gtrsim 12,000$ K), and a fixed temperature with 4000 K. With all the simulations presented in this paper and in Szulágyi et al. (2016a) and Szulágyi & Mayer (2016), we also created an empirical formula to estimate the CPD mass for observations, based on the protoplanetary disk mass and the planet mass. The subdisk characteristics we found can furthermore provide predictions for observational efforts to detect these disks, as well as help understand when and where satellites could form inside them.

## 2. Method

We carried out the 3D radiative hydrodynamics simulations with the JUPITER code (de Val-Borro et al. 2006; Szulágyi 2015; Szulágyi et al. 2016a) that was developed by F. Masset and J. Szulágyi. This code is grid-based, solves the continuity and Navier-Stokes equations, the total energy equation, and the radiative transfer with flux-limited diffusion approximation according to the two-temperature approach (e.g., Kley 1989, Commerçon et al. 2011). With the nested-meshing technique, it is possible to place high-resolution meshes around the planet to zoom into its vicinity (similarly to adaptive mesh refinement, but around a single location in the grid), with having the entire CSD still simulated on the base mesh with lower resolution. In this way, our maximum resolution in the planet vicinity was $\sim 80\%$ of a Jupiter diameter, roughly 112,000 km for a cell diagonal. This sub-planet resolution allows us to examine the circumplanetary gas in unprecedented detail.

Each simulation was made in the same way, according to the following procedure (similarly to Szulágyi et al. 2016a). First, a minimum mass solar nebula (i.e., $\sim 11 M_{\text{Jup}}$) CSD is simulated between 2.08 au to 12.40 au (sampled in 215 cells), with an initial $7.4^\circ$ opening angle (from the midplane to the disk surface, using 20 cells). We applied a constant kinematic viscosity, which equals a 0.004 $\alpha$-viscosity at the planet location. The initial surface density is a power-law function of radius with exponent $-0.5$ and equals 2222 kg m$^{-2}$ at the planet location. The initial disk aspect ratio is uniform and equal to 0.05. We ran this initial setup for 150 orbits with only two cells in the azimuthal direction ($\pi/2$ each) in order to reach thermal equilibrium in the azimuthally symmetric CSD. As the heating and cooling effects balance each other, the CSD evolves and finds a new equilibrium. In the next step, after the thermal equilibrium of the protoplanetary disk had been reached, we repositioned the cells azimuthally for the final resolution (680 cells azimuthally over $2\pi$), and a point-mass planet was placed at 5.2 au. This planet was gradually built up to the final mass during 30 orbits. In this way, the simulation was ran with only the base mesh for 150 orbits until we found that the planetary gap profile did not evolve anymore, at which point we began placing the nested meshes around the gas giant to enhance the resolution. The nested meshes were placed gradually after each other when steady state had been reached on a given level. This usually took a few orbits on each mesh from level 1 till 6. The results were typically obtained between the 240th and the 250th orbits. To avoid singularity at the planet point-mass location, the gravitational potential of the planet was smoothed with the commonly used epsilon-smoothing technique:

$$U_p = \frac{GM_p}{\sqrt{x^2 + y^2 + z^2 + \epsilon^2}}. \quad (1)$$

This means that the planet potential ($U_p$) is shallower within a distance of $\epsilon$ in the intermediate vicinity of the planet point mass, i.e., within this short distance, the gravity of the Jupiter-mass planet is underestimated. Therefore, it is critical to set the smoothing length ($\epsilon$) as small as possible, but not so small that...
it leads to numerical problems and inaccuracies. Because our resolution doubled on each nested mesh, we set different smoothing lengths on the various levels, a few times of the cell diagonals on a given grid level, as described in Table 1 for the finest level smoothing lengths. At each level of refinement (except for the last level, level 6) the smoothing was reduced through a tapering function described in Szulágyi et al. (2014). For the boundaries and resolution of each refined level, we used the same as Table 1 in Szulágyi et al. (2016a). As we mentioned above, the resolution on the finest level (level 6) was \(~80\%\) of a Jupiter diameter \((\sim112,000 \text{ km})\) for a cell diagonal for all simulations.

The coordinate system was spherical, centered on the star, and co-rotating with the planet. The equation of state was ideal gas—\(P = (\gamma - 1)E_{\text{int}}\)—which connects the internal energy \((E_{\text{int}})\) with the pressure \((P)\) through the adiabatic index: \(\gamma = 1.43\). Thanks to the radiative module and the energy equation, the gas can heat up through viscous heating and adiabatic compression, and cool through radiation and adiabatic expansion. For opacities we used the Bell & Lin (1994) opacity table, where both the gas and dust opacities are included. In this way, even though no dust is explicitly simulated, the dust contribution to the temperature is taken into account through the dust-to-gas ratio. We chose a ratio of 0.01, i.e., equal to the interstellar medium value. The mean-molecular weight was set to 2.3, which corresponds to solar composition.

We carried out 12 different simulations of 1, 3, 5, and 10 \(M_{\text{Jup}}\) planets, with and without fixing the planetary temperature (Table 1). As was shown in Szulágyi et al. (2016a), with this sub-planet resolution simulations it is possible and important to parametrize the planet. For this, three basic parameters need to be fixed: the planetary mass, the planetary radius (equal to two cell radii, roughly \(3 R_{\text{Jup}}\) for all planetary masses), and the planet temperature. Given that in our simulations the planet parametrized in this way consists only of \(4^3 = 64\) cells, the planet temperature was assumed to be homogeneous within this sphere. Regarding choosing the planet temperature values, it is very difficult to estimate the young Jupiter temperature during its formation, when it was still embedded in hot gas and heavily accreted. We used estimates from planet interior and evolution models of C. Mordasini et al. (2017, in preparation) and Guillot et al. (1995), where the youngest age calculated was 1 Myr. Guillot et al. (1995) provide an effective temperature of 1000 K if Jupiter formed in vacuum, so we chose this planet temperature value as our lowest. The Mordasini et al. models, on the other hand, took into account that planets form in a background disk and they also have accretional luminosity, thus the effective temperatures of Jupiters range from 2000 to 8000 K in these calculations for 1 Myr. Hence, for the calculations with one Jupiter-mass, we chose the upper limit of 10,000 K as our hottest planet simulation, and we carried out an additional 8000, 6000, 4000, and 2000 K \(T_{\text{planet}}\) computations. As the planet radiates away its formation heat, it gradually cools during this young age, therefore our temperature continuance from 10,000 K to 1000 K can be understood as an evolutionary sequence. Regardless of the initial effective temperature of Jupiter, it had to pass through at least some of these temperature values, as the effective temperature of Jupiter today is only \(~124\text{ K}\) (Guillot et al. 2004). For the 3–10 \(M_{\text{Jup}}\) simulations it is even more difficult to estimate temperature values, given the fewer planetary interior calculations made in the mass regime. Moreover, the simulations are especially time-consuming for the higher planetary masses (because of the deeper gravitational potential of the planet), therefore we could not run as fine a planet temperature grid as we did in the cases of one Jupiter mass. We therefore made simulations without a temperature cap \((T_p > 12,000 \text{ K})\) and with 4000 K, given that higher mass planets \((\geq 3M_{\text{Jup}})\) should a priori be hotter at the same age than Jupiter-mass planets.

The benefits and disadvantages of using a temperature cap for the planets in the simulations are the following. First, the surface temperature of forming planets probably should not be higher than 8000 K because none of the current interior models predict this. Indeed, 8000 K is much higher than the Sun’s effective temperature. If the planets were that hot, observations could probably detect them even when these forming planets are embedded. However, there is no observational evidence of hot-spots of forming planets within the first million years of disk evolution. Second, letting the radiative module compute the temperature at the planet location is probably incorrect without a proper planet interior model. The first step toward setting up a planet in the disk simulations is exactly by fixing the temperature, mass, and the radius of the planet (that is, \(3 R_{\text{Jup}}\)). The low resolution inside the planet (four cells radially) meant that a more complex interior model could not be implemented because the resolution of planet phase transitions are insufficient and because of convective and radiative zones, etc. On the other hand, the temperature cap is an artificial energy sink that does not correspond to the local density value. However, along the similar idea, past hydrodynamic simulations often used mass sink cells to enforce or mimic planetary accretion. Considering all the advantages and disadvantages of using a temperature cap, here we discuss both types of models to show the similarities and differences with and without fixing the planetary temperature.

### 3. Results

#### 3.1. The Density of the Circumplanetary Gas and the Subdisk Mass

In this section we focus on the density distribution of the circumplanetary gas as well as on the mass of the Hill-sphere and the CPD. First, we show Jupiter-mass simulations with

| \(M_p\) \((M_{\text{Jup}})\) | \(T_p\) \((K)\) | Final Smoothing Length (cell diagonal) | \(\text{km}\) |
|-------------------|-----------------|---------------------------------|--------|
| 1                 | 10,000          | 6                               | \(6.57 \times 10^5\) |
| 1                 | 8000            | 6                               | \(6.57 \times 10^5\) |
| 1                 | 6000            | 6                               | \(6.57 \times 10^5\) |
| 1                 | 4000            | 6                               | \(6.57 \times 10^5\) |
| 1                 | 2000            | 6                               | \(6.57 \times 10^5\) |
| 1                 | 1000            | 6                               | \(6.57 \times 10^5\) |
| 3                 | non-fixed       | 12                              | \(1.31 \times 10^6\) |
| 3                 | 4000            | 12                              | \(1.31 \times 10^6\) |
| 5                 | non-fixed       | 12                              | \(1.31 \times 10^6\) |
| 5                 | 4000            | 12                              | \(1.31 \times 10^6\) |
| 10                | non-fixed       | 24                              | \(2.63 \times 10^6\) |
| 10                | 4000            | 24                              | \(2.63 \times 10^6\) |
various planetary temperatures, then the 3–10 Jupiter-mass simulations with and without the planetary temperature cap.

3.1.1. Subdisk Mass and Density of Jupiter-mass Planets with Various Planetary Temperatures

Our previous study (Szulágyi et al. 2016a) showed that the gas temperature can be so high around a Jupiter-mass planet that the envelope around the gas giant cannot collapse into a CPD. Thus, depending on the temperature, we might get a CPD or a circumplanetary envelope, even around giant planets (see also in Ormel et al. 2015a, 2015b and D’Angelo & Bodenheimer 2013). However, the exact temperature at which this transition occurs between 2000 and 13,000 K and the rapidity of this change required further simulations with various planet temperature values in between, and these are shown here.

Figure 1 shows the density, temperature (see Section 3.2), and normalized angular momentum (see Section 3.3) vertical slices in the planet vicinity for the six simulations with various planetary temperatures in increasing order. All color scales are fixed to a minimum and a maximum value, therefore the color differences and the contrasts for the various simulations can be compared. The figures purposefully show only one snapshot in the end of the simulations, in order to show the details of the gas dynamics that are due to the high resolution, which would be wiped away by averaging the snapshots in time.

The first column in Figure 1 represents the density color-maps in decreasing $T_p$ order. We can follow the transition from a circumplanetary envelope to a CPD as the temperature of the gas giant decreases. It is a quite continuous transition, therefore it is difficult to set one point where the transition from disk to envelope occurs, there are clearly “disky-envelope” cases based on the density maps. However, with the help of the 1D midplane density profile (see Figure 2), we can set a limit between $T_p = 6000$ and $T_p = 4000$ K because the midplane density distribution of the circumplanetary gas is significantly different for the 10,000–6000 K $T_p$ models and the 4000–1000 K simulations. These density profiles are averaged in time over one orbit of the planet (sampled in 21 epochs), and they show the entire Hill sphere on the midplane, with the planet on the left-hand side and the edge of the Hill sphere on the the right-hand side. From Figure 2 it is clear that the inner parts of the subdisks or envelopes contain most of the mass of the Hill sphere. In other words, the profile is peaky as we approach the planet.

To compute the mass of the CPD, the limits of the subdisk need to be defined. Szulágyi et al. (2014) described three different methods. The first is using the normalized angular momentum of the subdisk (see the detailed definition in Section 3.3), i.e., setting a minimum threshold for the rotation. In the locally isothermal simulations of Szulágyi et al. (2014), the limit was 65% sub-Keplerian rotation or more, but as the third column in Figure 1 shows, as the planet temperature decrease, the rotation of the subdisk enhances. This means that it would be difficult to set a minimum normalized angular momentum value that would fit all our simulations. The second method for defining the borders of the subdisk could be to compute the eccentricity of a fluid element with respect to the distance to the planet. Szulágyi et al. (2014) chose to define the radial extent of the CPD based on where the orbits of the fluid elements are circular. However, the subdisk can be eccentric (Kley & Dirksen 2006; Dunhill 2015), therefore this definition can be too restrictive. The third possibility is drawing the streamlines of the flow around the planet and define the CPD where the streamlines bound to the planet. However, defining a time-constant 3D surface in this way is a difficult task. A more comprehensive way to define the subdisk borders is therefore based on a minimum density, i.e., an isodensity surface. In this work we decided to use this technique with a density threshold of $>1.27 \times 10^{-8}$ kg m$^{-3}$, also taking into account where the gas significantly rotates around the planet (see Section 3.3, the first column in Figure 8). This value means a $\sim 0.6 R_{\text{Hill}}$ radial extent on the midplane, which is consistent with the place where the radial velocity changes sign (see Section 3.3 with Figure 9). This value is in agreement with 2D simulations, e.g., Crida et al. (2009). The inner radius of the CPD in our calculation was defined at the smoothing length because the mass within this area would have already been accreted by the planet.

The subdisk masses are shown in Table 2, where the values correspond to an average value over one orbit of the planet sampled 21 times, and the standard deviation of these are the error bars on the average value. Given that the density profiles are so steep (see Figure 2), it has no significant importance where (at what minimum density) the outer limit of disk is defined, since most mass is in the inner subdisk. Because the CPD boundaries are arbitrary either way, we also computed the Hill-sphere masses in all simulations (see in Table 2). The Hill sphere can be defined quite precisely with $R_{\text{Hill}} = a_p (M_p/3M_\ast)^{1/3}$ as long as the planet mass is significantly lower than the stellar mass, like in our case (0.001 planet-to-star mass ratio). In the case of the Hill-sphere mass computation, we integrated the mass of all (entire) cells inside the Hill sphere, including the mass within the smoothing length, which was not considered for the subdisk mass. From Table 2 one can see that there is a significant difference between the Hill masses of the disky cases (1000 K $\leq T_p \leq 400$ K) and the envelope cases (6000 K $\leq T_p \leq 10,000$ K). The disky cases have a low-mass Hill sphere, roughly $3 \times 10^{-3} M_{\text{Jup}}$, while the envelope cases are almost three times more massive with $\sim 8 \times 10^{-3} M_{\text{Jup}}$. This is most likely a geometric effect: the envelope cases fill up the Hill sphere spherically, while the disk cases have a low-density cone above the CPD, where the vertical influx penetrates.

The subdisk masses for the $T_p = 4000$, 2000, and 1000 K simulations are $\sim 1.3 \times 10^{-3} M_{\text{Jup}}$, with a slight decline with decreasing planetary temperature, but this cannot be conclusive because of the large error bars. The Hill-sphere mass also decreases in the same way, however, which supports this trend. If this is a true relationship, it can be understood again with the geometry: the disks around cooler planets are thinner, the low-density cone of the vertical influx is wider, filling up the Hill sphere less than in the hotter planet simulations. The radial extents of the CPDs are roughly 0.6 $R_{\text{Hill}}$, similarly to the findings of Szulágyi et al. (2014), but slightly larger than 0.1–0.3 $R_{\text{Hill}}$ of Tanigawa et al. (2012) and Ayliffe & Bate (2009b).

3.1.2. Subdisk Mass and Density of Planets with 3–10 Jupiter Masses

In all the high-mass planet cases, a CPD formed around the gas giant (see Figure 3). As Figure 4 shows, there is no significant difference between the high-mass planet cases on the midplane density of the CPDs. The mass of the planet seems to be less important for setting the density structure than the planetary temperature. The density threshold for defining the
Figure 1. Volume density (first column), temperature (second column), and normalized angular-momentum (third column) color maps of the planet vicinity.
Figure 2. Midplane density profile in the Hill sphere of the Jupiter-mass planet with various planetary temperatures from 10,000 K to 1000 K. The profile is averaged over 21 outputs of the simulation during one orbit of the planet. There is a clear difference between the simulations of \( T_p = 10,000-6000 \) K and the 4000–1000 K cases, hence one can say that the transition from envelope to disk occurs between planetary temperatures of 6000 and 4000 K.

| \( T_p \) (K) | CPD Mass \((10^{-3} M_{\text{Jup}})\) | Hill-sphere Mass \((10^{-3} M_{\text{Jup}})\) |
|---|---|---|
| 10,000 | ... | 7.11 ± 0.132 |
| 8000 | ... | 8.09 ± 0.199 |
| 6000 | ... | 9.11 ± 0.302 |
| 4000 | 1.342 ± 0.324 | 3.49 ± 0.383 |
| 2000 | 1.254 ± 0.314 | 3.00 ± 0.455 |
| 1000 | 1.279 ± 0.066 | 2.79 ± 0.192 |

Table 2: CPD and Hill-sphere Masses for Planets of One Jupiter mass

In all our simulations the inner CPD or -envelope is hotter than the planet itself, similar to the work of Zhu (2015). This is probably an artifact of the temperature cap, as we also show in Section 3.2.2. As photons try to escape from this overheated region, they could move toward the planet and heat it, or they
could flee toward the cooler regions of the outer CPD. However, the temperature cap on the planet region means that instead of these photons heating the planet, we artificially fix the temperature and thereby create a kind of energy sink. As we show in Section 3.2.2 for planets with 3–10 Jupiter masses, where temperature cap was not set, the planet is always hotter than the CPD.

Given that all in our simulations the CPD is hot, this means that it can significantly contribute to the observed luminosity of directly imaged embedded planets. This detection method uses the observed brightness to calculate the luminosity of the planet, which is then used to estimate the planetary mass. These planets are often still surrounded with hot gas and dust, as observations of thermal emission in the intermediate vicinity

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**Figure 3.** Zoom-in of the circumplanetary disk that is seen face-on (midplane cut, on the left-hand side) and through a vertical slice (right-hand side) for the 3–10 $M_{\text{Jup}}$ planets. In all cases a circumplanetary disk formed around these high-mass gas giants. The flaring of these disks is larger with higher planetary mass.
of several planets suggest (e.g., Reggiani et al. 2014; Quanz et al. 2015; Sallum et al. 2015). However, in the luminosity estimation—therefore in the planetary mass estimation as well—the contribution of the CPD or envelope is not taken into account (see also in Montesinos et al. 2015). In this work we showed that this circumplanetary gas is hot at the first 1 Myr of evolution, therefore it certainly contributes to the observed luminosity, which might result in an overestimation of the mass of directly imaged planets that are still embedded in their protoplanetary disks.

It can also be concluded that the temperature of the circumplanetary gas is heated mostly by the local processes, e.g., adiabatic compression due to the accretion process, irradiation of the forming planet itself, and shock heating and viscous heating within the disk. This suggests that the gas in the CPD will be hotter and more luminous than the background CSD in the vicinity, even if the planet is far away from the star. These hot and more extended CPDs at large orbital distances could therefore be easier to detect than those located closer in. Nevertheless, some heating mechanisms also decrease with orbital distance (e.g., the turbulent viscosity), so adequate simulations with large orbital separation planets are needed to study the temperature dependence of CPDs.

The temperature is so high in the circumplanetary gas in all our simulations that dust condensation (around 1500 K) can only occur beyond 0.04 \( R_{\text{Hill}} \) for the \( T_p = 1000 \) K simulation and \( >0.1 \, R_{\text{Hill}} \) for the 10,000 K planet temperature case. As the planet cools off, the inner radius where the temperature is sufficiently low for satellites to form therefore approaches the planet. This suggests that, e.g., the satellites of Jupiter had to form in the outer CPD and migrate inward. In addition, the \( \text{H}_2\text{O} \) snow line is beyond the borders of the CPD in all of our models, therefore none of them are sufficient to form the Galilean satellites at this evolutionary stage. The absolute inner radius where satellites are capable to form is defined by the Roche limit, within which the satellites would fragment as a result of tides. When we calculate with \( R_p = 3R_{\text{Hill}} \) a planet-to-satellite density ratio of 0.44, this would give for our Jupiter mass planet a 0.007 \( R_{\text{Hill}} \), which is within the silicate condensation line for all of our models. From all this it can also be assumed that satellite formation occurs rather late, when the gas temperature in the subdisk has significantly decreased from these original high values.

Satellites in the gaseous CPD can migrate inward or outward, depending on the total torque they experience. Depending on whether the proto-satellite is capable of opening a gap in the CPD, it migrates according to Type II (gap-opening) or Type I (no gap) regime (e.g., Lin & Papaloizou 1985; Tanaka et al. 2002; Paardekooper et al. 2011; Baruteau & Masset 2013). In our simulations we found the CPDs to have low gas density, and because the turbulent viscosity should be very low (Fujuji et al. 2011, 2017) as well, the proto-satellites could easily open gaps as long as the disk aspect ratio is not too high. Hence, they would most likely migrate according to the Type II regime (Hasegawa & Ida 2013; Miguel & Ida 2016; Fujii et al. 2017). The recent findings of Fujii et al. (2017) are that the migration direction of an Io-sized body is toward the planet in the bulk of the CPD, but the direction is outward in the outer disk. A self-consistent migration study that also includes satellite growth is needed to answer the migration direction and speed in our CPD models. This will be part of a future paper.

Regarding the ionization and viscosity of the subdisk, the previous locally isothermal work of Szulágyi et al. (2014) suggested that the CPD might have vanishing viscosity because planets form in dead zones and the subdisk is shielded from the stellar ionizing photons by the inner CSD (e.g., Iglner & Nelson 2008; Pierens & Nelson 2010; Gressel et al. 2012; Baruteau et al. 2016). The zero-viscosity assumption was likely incorrect, as the high temperatures observed in this simulations can ionize the gas at certain places (in the very inner part of the CPD and in the shock front in the top layer of the subdisk (see Szulágyi & Mordasini 2016), which suggests that turbulent viscosity that is due to the magnetorotational instability might be at work in such places. However, recent works of Fujii et al. (2011) and Fujii et al. (2014) argued that it is difficult to imagine that magnetorotational instability takes place in the bulk of the subdisk and drives the accretion as the main angular momentum transport mechanism. Several other instabilities were discovered in CSDs to transport angular momentum (Baruteau et al. 2014), which might work in similar ways in the CPD, such as spiral wave instability (Ba et al. 2016), vertical shear instability (e.g., Nelson et al. 2013; Barker & Latter 2015; Richard et al. 2016), and disk wind (e.g., Suzuki & Muto 2010; Suzuki & Inutsuka 2014; Gressel et al. 2015). For the CPD, the spiral wake is also thought to promote accretion (Szulágyi et al. 2014; Zhu et al. 2016).

![Figure 4](image.png)

**Figure 4.** Density profile of the midplane for the high-mass planets (3–10 \( M_{\text{Jup}} \)).

**Table 3**

| \( M_p \) \((M_{\text{Jup}})\) | \( T_p \) \((K)\) | CPD Mass \((10^{-3} \, M_{\text{Jup}})\) | Hill-sphere Mass \((10^{-3} \, M_{\text{Jup}})\) |
|---|---|---|---|
| 3 | non-fixed (12854) | 6.97 ± 0.24 | 13.08 ± 0.36 |
| 3 | 4000 | 6.73 ± 0.17 | 14.73 ± 0.39 |
| 5 | non-fixed (19885) | 10.84 ± 0.44 | 19.70 ± 0.71 |
| 5 | 4000 | 23.11 ± 0.53 | 34.39 ± 0.76 |
| 10 | non-fixed (16842) | 40.07 ± 1.18 | 115.99 ± 2.81 |
| 10 | 4000 | 29.56 ± 0.38 | 63.06 ± 0.95 |
The high temperatures in the planet vicinity can alter the planet migration as well, as numerous works have pointed out (e.g., Pierens et al. 2012; Baruteau & Masset 2013; Lega et al. 2014, 2015; Benítez-Llambay et al. 2015, 2016; Masset & Velasco Romero 2017). The planet temperature probably has even a higher effect on satellite migration, as it affects the entire circumplanetary gas.

3.2.2. Subdisk Temperature of Planets with 3–10 Jupiter Masses

For planets with 3–10 Jupiter masses, the midplane temperature profile (Figure 7) in the inner 2% of the Hill sphere is heavily affected by the planetary temperature; this is less significant in the outer parts of the Hill sphere. From Figure 7 it is obvious that the inner CPD is hotter than the planet in the fixed planetary temperature simulations, but this is not the case when we do not set a temperature cap. This proves that the planet indeed has to be always hotter than its disk, and the inner overluminous CPD is just an artifact of simulations with fixed temperatures.

Even though these temperature profiles are also averaged over one orbit of the planets sampled in 21 epochs, the curves seem to be much rougher, like in the case of Jupiter-mass planets in the previous subsection. The reason is that in the case of the high-mass planets, the gap and hence the CPD becomes more and more eccentric and is tidally stripped by the protoplanetary disk (see in Section 3.4.2). This violent interaction with the CSD over one orbit of the planet—while...
the CPD rotates orders of magnitude times more—is visible in the temperature profiles.

The location of the dust sublimation line (\(\sim 1500 \text{ K}\)) within the subdisk varies by between 0.07 and 0.11 Hill radii with increasing planetary mass. This tells us that the satellites can form only in the outer CPD, and they have to form even farther away as the planetary mass is higher. The water snow-line is just within the CPD borders for the 10 \(M_{\text{Jup}}\) planet. It is slightly beyond the subdisk limits for the 3–5 \(M_{\text{Jup}}\) gas giant. The reason for this that the Hill sphere of the planet with 10 Jupiter masses is much larger in physical length than the lower mass planet Hill spheres.

The shock front at the top of the CPDs is much stronger with increasing planetary mass (Szulágyi & Mordasini 2016). The ionization of hydrogen can be so high in the shock of the 10 Jupiter-mass case that \(H\alpha\) can arise from there. As the gas passes through the shock front, it loses entropy, so the gas that is eventually accreted by the planet will have a much lower entropy than without the shock front on the subdisk (Owen & Menou 2016; Szulágyi & Mordasini 2016).

### 3.3. Kinematic Properties

#### 3.3.1. Subdisk Velocity and Angular Momentum of Jupiter-mass Planets with Various Planetary Temperatures

The third column in Figure 1 shows the normalized angular-momentum color maps. These are the \(z\)-components of the angular momentum relative to the planet and normalized with the local Keplerian rotation. The result is therefore a number between 0.0 and 1.0, where the latter means that the gas rotates with Keplerian orbital velocity at that location (with \(r\) the distance from the planet). Gas disks are usually sub-Keplerian, i.e., the gas rotates more slowly than the local Keplerian rotation at every radius from the planet (or star). In the third column of Figure 1 one can indeed observe that the circumplanetary gas is sub-Keplerian, but rotates faster as the planet temperature drops. This is because it becomes more and more pressure supported as \(T_p\) increases, hence the rotation slows down, and a pressure-supported envelope forms. In the \(T_p = 10,000 \text{ K}\) case the rotation of the envelope almost stalls. For observational efforts of the CPD, all this means that the kinematic fingerprint of the circumplanetary gas (i.e., its rotation) is more obvious if the planet is colder, therefore it is easier to distinguish the CPD kinematically from the surrounding CSD, similarly to what Perez et al. (2015) found. In other words, the more evolved (colder) planetary systems are good targets for detecting the subdisk kinematically.

We compare the three different velocity components—radial, azimuthal, and colatitude velocities—in Figure 8 for the different simulations. In the first column one can see the radial velocity defined with respect to the star, therefore the left side of the planet (that is, toward the star) is mainly negative (blue) radial velocity and the right side of the planet (toward the outer CSD) is positive (yellow): the CPD rotates in a prograde direction. In this figure with the various planetary temperatures it can be already seen that the radial velocity increases as \(T_p\) drops. In the 1D averaged radial profiles (see Figure 9) this is even more obvious. The rotation peaks with 7 km s\(^{-1}\) for the 1000 K planetary temperature model near the gas giant, while the maximum decreases and is located farther and farther away from the planet for \(T_p = 2000 \text{ K}\) and \(T_p = 4000 \text{ K}\). For the hotter models (\(T_p \geq 6000 \text{ K}\)), something different occurs: the local maxima of the radial velocity are not in increasing or decreasing order with \(T_p\). This is because in these cases we trace convection in the envelope within \(\sim 0.2 R_{\text{Hill}}\) as the radial velocity profiles “wobble” several times (see also Szulágyi et al. 2016a). The envelopes are too hot, therefore in order to cool, convection starts in the inner parts. Still, the entire envelope slowly rotates with differential rotation, mostly in prograde direction. The convective motion is beautifully evident in the second column of Figure 8, which represents the azimuthal velocity. Here we can observe a spherical area with a checkerboard pattern in the immediate vicinity of the planet within 0.1 \(R_{\text{Hill}}\). This pattern shows the convective cells. As the planetary temperature decreases, the area where convection occurs shrinks, but even in the disk cases (1000 K \(\leq T_p \leq 4000 \text{ K}\)) it can be found. This means that the CPD has a substructure; its inner part is always an envelope around the planet with a radius ranging from a few Jupiter radii to a few tens of Jupiter radii, depending on \(T_p\), and within this area, convection could occur. Since between the different simulations only \(T_p\) is varied, the size of this envelope is likely set by the pressure that is due to heating and the gravitational potential of the planet. The balance of these two forces determines whether the circumplanetary gas is in the form of an envelope or a disk.

The azimuthal velocity profiles (Figure 10) again show the convective wobbles for the 10,000 K to 6000 K planetary temperature simulations and the rotation with 5.5–7 km s\(^{-1}\) peak velocities for the \(T_p = 1000, 2000,\) and 4000 K models.

The colatitude velocity color-maps (third column on Figure 1) show the velocity of the vertical influx of gas through the planetary gap. The velocity direction toward the midplane is shown in yellow (positive colatitude velocity). This flow feeds the CPD and arises from the top layers of the CSD (see also in Szulágyi et al. 2014). As it hits the disk, it creates a shock surface at the top of the subdisk (Szulágyi & Mordasini 2016). From this decreasing \(T_p\) sequence of Figure 1, it is clear that the vertical influx shocks closer and closer to the planet in the colatitude direction, while its speed also enhances. In the envelope cases (10,000–6000 K planet temperature models), the convection cells are again visible in an area within \(\sim 0.1 R_{\text{Hill}}\). The shock front advance toward the planet is also obvious in the colatitude velocity profiles in Figure 11. In our hottest model (\(T_p = 10,000 \text{ K}\)) the shock front is not visible at all any longer, here the local maximum on the right-hand side with 0.7 km s\(^{-1}\) is the convective motion in the envelope. On the other hand, in the coldest case (\(T_p = 1000 \text{ K}\)), the peak velocity of the vertical influx reaches \(>13 \text{ km s}^{-1}\), almost twice the rotational speed. From the observational perspective, detecting the CPD kinematically (in contrast with the surrounding CSD’s kinematics), the vertical velocities are an even better choice than the rotational velocities suggested by Perez et al. (2015). Furthermore, this vertical velocity is so high that it might be possible to observer the redshift or broadening of certain spectral lines, similar to photoevaporative flows (e.g., Pascucci et al. 2011).

#### 3.3.2. Subdisk Velocity of Planets with 3–10 Jupiter Masses

Around these high-mass planets, a CPD forms always, even if the planetary temperature exceeds 12,000 K. As in the case of the Jupiter-mass planets, the vertical influx shocks closer to the gas giant when the temperature of the planet is lower (Figure 12). In addition to the temperature effect, there is of
Figure 8. Radial velocity (first column), azimuthal velocity (second column), and colatitude velocity (third column) color-maps of the planet vicinity.
course an effect of the planetary mass—or rather the choice of the smoothing length of the gravitational potential. This highlights that for 3D hydrodynamic simulations the smoothing length can affect the outcome of the simulation, therefore a priori, one should use as a small smoothing length as possible. On the other hand, this will enormously slow down the simulations, especially for high planetary masses, like in our case. A better prescription for the softening of the gravitational potential is needed.

The vertical influx velocity peaks between 12 and 22 km s$^{-1}$ for planets with 3–10 Jupiter masses. The higher the ratio of planetary mass to smoothing length ratio, the higher is the velocity. The redshift of certain forbidden lines (such as

Figure 9. Radial velocity profile with respect to the radius from the star. The radial velocity is defined with respect to the star, not the planet.

Figure 10. Azimuthal velocity profile vs. the azimuth.

Figure 11. Colatitude velocity profile with respect to the colatitude itself. This shows the increase in vertical influx velocity by approaching the planet (which is at the right end of the figure in the midplane). In the case of the circumplanetary disks ($1000 \text{ K} \leq T_p \leq 4000 \text{ K}$), this flow is supersonic, and it creates a shock front on the surface of the circumplanetary disk; here the velocity is the maximum. It can be as high as 10–13 km s$^{-1}$, which might be detectable by the redshift or broadening of certain spectral lines that arise from the shock front. This shock front approaches the planet as the planet temperature decreases and the shock itself is becomes increasingly stronger and the velocities are higher. In the case of the circumplanetary envelope ($6000 \text{ K} \leq T_p \leq 10,000 \text{ K}$), we do not have a shock front any longer and can only see convection in the envelope as the highest speed motion, therefore the colatitude velocity is low (0.7 km s$^{-1}$ maximum).

Figure 12. Colatitude velocity profile (vs. colatitude) for the high-mass planets (3–10 $M_{\text{Jup}}$).
Ne II, Ne III, and Ar II—Pascucci et al. 2011) might be detectable with current spectrographs, such as VISIR on the VLT. Accretion tracer line emission (Hα, Paβ, Brγ) might also be expected. This emission has been detected in the case of the planetary candidate LkCa15b by Sallum et al. (2015) with the Magellan Adaptive Optics System in Simultaneous Differential Imaging mode, but the SPHERE instrument also has the spatial resolution to search for some of these emission lines.

Regarding the rotational velocities, both the radial and azimuthal velocities are higher of course, than in the case of Jupiter-mass planets. The peak values are 12, 10.5, 7.6 km s⁻¹ for the 10, 5, 3 M_Jup planets respectively.

3.4. Gap Profile

3.4.1. The Gaps of Jupiter-mass Planets with Various Planetary Temperatures

Given that our simulations contain an entire CSD, we also examined the planetary gap structure for the different simulations. We integrated the volume density in the colatitude direction on the base mesh, then averaged azimuthally. We also plotted, but the other simulations qualitatively show the same. The reasons for the difference with some previous works, such as Fung & Chiang (2016), is that we use here radiative simulations, while Fung & Chiang (2016) used only a locally isothermal equation of state. In a locally isothermal setup, there is per definition no vertical temperature gradient inside the CSD, therefore the gap width must be the same at all colatitudes, as was shown by Masset & Benítez-Llambay 2016 (their Figure 2 and relevant text). This conservation of the Bernoulli invariant (Equation (15) in Masset & Benítez-Llambay 2016) is the reason why isothermal 2D gap widths are the same as isothermal 3D gap widths. However, in radiative simulations—as could be the case for real CSD (Woitke et al. 2009)—there is a vertical temperature gradient and the Bernoulli invariant is not conserved because of radiative dissipation (cooling through radiation), hence the gap width has to change at different colatitudes. If one integrates such a 3D disk the migration of the planet inside the CSD. In the case of giant planets, the torque also drives the gap opening, hence the change in planet temperature/luminosity can affect the gap properties.

We also examined the structure of the (gas) gap at different colatitudes. This was motivated by the fact that some works have found that 3D gaps differ from 2D gaps (Kley et al. 2001; Morbidelli et al. 2014; Masset & Benítez-Llambay 2016), while others obtained the opposite, see Fung & Chiang (2016). Hence, we studied the question by azimuthally averaging the volume density at different colatitude slices of the CSD. We show in Figure 14 the change in gap profile at different colatitudes for the T_p = 1000 K simulation. In agreement with Morbidelli et al. (2014), we also found that the gap is wider when moving away from the midplane in colatitude direction, hence the gap indeed seems to have a 3D profile and ought to differ from 2D solutions. Moreover, the depth of the gap also varies with colatitude distance. In Figure 14 only one simulation is plotted, but the other simulations qualitatively show the same.

Figure 13. Gap profile of the different simulations. The temperature of the planet affects the structure of the gap. The colder the planet, the deeper and wider the gap.

Figure 14. Gap profile at different colatitude values (only azimuthally averaged for the volume density). The gap depth and width vary when moving away from the midplane; the gap has a 3D structure and does not act like 2D gaps.
vertically, the gap will be of different depth and width than in a corresponding radiative 2D calculation that traces only the midplane.

For observational purposes, we would like to emphasize that gas gaps differ from dust gaps in depth and width (e.g., Tanigawa et al. 2014; D’Angelo & Podolak 2015; Rosotti et al. 2016). In this paper we discuss the gas gaps, therefore only the micron-sized dust particles, which are well coupled to the gas, can have the same distribution as the gas gap. Larger particles (mm, cm, and beyond) usually produce wider and deeper gaps. In general, even low-mass planets can open gaps in the >mm dust (e.g., Paardekooper & Mellema 2006; Dipierro et al. 2016), while only giant planets (beyond ~Saturn mass) can open gas gaps.

3.4.2. Gaps of Planets with 3–10 Jupiter Masses

The gap of our planets with 3–10 Jupiter masses is eccentric, as was shown before by various studies (e.g., Bryden et al. 1999; Kley 1999; Lubow et al. 1999; Kley & Dirksen 2006; Lubow & D’Angelo 2006). It is known that the eccentricity of the gap is higher with the planetary mass inside the same CSD and around the same star (see Figure 15). Moreover, the CSD precesses around the star-planet system and itself becomes eccentric as well. This effect is smaller in 3D than in 2D (Kley & Dirksen 2006), but nevertheless always present. We computed the eccentricity of each cell (fluid element) on the midplane around the planet within the Hill sphere; these eccentricities can been seen in Figure 16. We found that the CPD eccentricity is minimum between ~0.1–0.3 Hill radii, but even in this region, the eccentricity varies between 0.1 and 0.3.

The eccentric CPD means that over one rotation of the CSD—which is orders of magnitude more rotation for the CPD—the subdisk changes violently as it is pulled and truncated by the tidal forces. Satellite formation might be cumbersome in such disks, as long as the CSD is present. After the protoplanetary disk dissipates, the perturbation stops, therefore satellite formation is more viable.

Figure 17 shows the gap profile of the high-mass gas giants at various phases during one orbit: the gap width and depth clearly change rapidly and more violently with higher planetary mass, similarly to the findings of previous works (e.g., Kley 1999; Lubow et al. 1999; Kley & Dirksen 2006; Lubow & D’Angelo 2006). For observations of young planetary systems, this means that estimating the mass of the planet simply from the gap depth and width is a very tricky task. Not only do the dust and gas gaps differ significantly for a given mass object, but when the planet has high mass, the gap structure changes rapidly.

In Figure 18 we averaged the planetary gap profiles of the 3–10 M_{\text{Jup}} planets over one orbit of the planet. The asymmetry of the left- and right-hand side of the planetary gap is also due to the eccentricity and precession of the CSD. That the gap is wider with planetary mass is expected (Crida & Morbidelli 2007; Zhu et al. 2013; Fung et al. 2014; Duffell 2015). As in the previous section for the Jupiter-mass planet, here again the lower the temperature of the planet, the deeper the gap even for the 3–10 M_{\text{Jup}} planet-mass regime. This indicates that as planets cool off during their evolution, their gap becomes somewhat deeper (not even mentioning that as the CSD dissipates, the gaps also groove even more substantially).

3.5. The Subdisk-mass Function

We have seen in Section 3.1.2 that the CPD mass scales with the planet mass, i.e., the more massive planets have more massive subdisks in the same protoplanetary disk. Moreover, Szulágyi & Mayer (2016) recently showed that the subdisk mass from radiative simulations also scales with the CSD mass because the latter feeds the former. It can also be concluded from Section 3.1.2 and Szulágyi & Mayer (2016) that the CSD mass is equally important in setting the CPD-mass as the planetary mass. This also means that it is well possible to find a more massive subdisk around a Jupiter-mass planet in a high-mass CSD than around a planet with 5 Jupiter masses in a low-mass CSD. Furthermore, this also

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1 The fact that the CPD surface density scales with the CSD surface density is trivial in the case of locally isothermal simulations. However, for non-isothermal simulations, the form of the scaling law is not that obvious any longer.
indicates a significant mass-evolution of the subdisk as the CSD vanishes, and therefore the feeding of the CPD decreases. Because the CPD mass depends on the planet mass and on the CSD mass, we used our simulations presented in this paper, in Szulágyi et al. (2016a), and in Szulágyi & Mayer (2016) to empirically fit a function for $M_{\text{CPD}} = f (M_{\text{CSD}}, M_p)$. Again, because our definition of CPD is arbitrary, this function is also determined for the Hill-sphere mass, which in contrast is a well-defined quantity. Because we found that the $M_{\text{CPD}}/M_{\text{CSD}}$ ratio is very low, we estimated the function in the following form:

$$M_h = 5.38 \times 10^{-4} M_{\text{CSD}} M_p - 3.71 \times 10^{-4} M_{\text{CSD}}, \quad (6)$$

$$M_{\text{CPD}} = 3.17 \times 10^{-4} M_{\text{CSD}} M_p - 4.33 \times 10^{-4} M_{\text{CSD}}, \quad (7)$$

where all masses are in Jupiter-mass units. We show the data and fitted functions in Figure 19.

It is possible to increase the goodness of the fit with higher-order polynomials, but given the few data points and the lack of known physical relation between $M_{\text{CPD}}$, $M_{\text{CSD}}$, $M_{\text{planet}}$, we do not feel justified to enter into such a discussion. The above equations can provide a useful, if rough, estimation of the CPD mass for observation planning.

It is interesting to consider that in case of the solar system, the integral mass of the satellites of Jupiter and Saturn are constants of $2 \times 10^{-4} M_p$, which implies that the CPD/planet mass ratio could have been constant. However, we see from this work and the results of Szulágyi & Mayer (2016) that for the same massive planet, the CPD mass can be different when the CSD has a different mass. This means that if this relation exists, it is rather $M_{\text{CPD}}/M_p/M_{\text{CSD}}$ constant at the time of the satellite formation. The CPD/planet/CSD mass ratio from all of our simulations gives a low value of between 2 and $4 \times 10^{-4}$, but of course does not prove a law.

4. Conclusions and Discussion

We performed 3D radiative hydrodynamics simulations of 1, 3, 5, and 10 Jupiter-mass planets with sub-planet resolution and varied the temperature of the planet. For the 1 $M_{\text{Jupiter}}$ gas giant we simulated an evolutionary sequence of planet temperatures from 10,000 K down to 1000 K, representing how the planet radiates away its formation heat. For the higher mass planets (3–10 $M_{\text{Jupiter}}$), we only examined two $T_p$ cases, a varying planetary temperature case, where the temperature peaked at higher than 12,000 K and a fixed 4000 K cap. We examined the CPD or envelope characteristics based on the planetary temperature. Given that our simulations include an entire CSD as well, we also studied the planetary gap structure.

This work is motivated by two reasons. First, we would like to help observational efforts of CPDs by unveiling their
Second, the characteristics of the subdisk are also constrained where and when the satellites can form in these disks. Whether a planet can form a disk or an envelope depends on the balance between the gravitational forces and the pressure that is due to heat (e.g., Szulágyi et al. 2016a). If the latter dominates, the outcome is a pressure-supported envelope. Our simulations revealed that for a planet with one Jupiter mass, the transitions from envelope to disk state occur continuously, but mainly between 6000 and 4000 K. For the higher mass planets, we observed CPDs even when the planet was cooler. Nevertheless, in all cases the entire subdisk temperature was higher than the water freezing point (~180 K), and the inner 10% of the Hill sphere even above the silicate sublimation point. This suggests that satellite formation cannot occur at this early evolutionary stage (<1 Myr) of the CPD, only much later. The temperature profiles of the disks were always very steep, suggesting that the conditions for satellite formation are first adequate in the outer CPD; satellites form there and migrate in later on.

The high temperature of the CPDs suggests high luminosity, similar to what Zhu (2015) and Szulágyi & Mordasini (2016) found. This is important for the direct detection of young embedded planets because their planetary mass estimate is based on the observed luminosity, where the subdisk contribution is not taken into account. This can lead to an overestimation of planetary masses from direct-imaging observations of embedded planets.

The CPD mass was found to scale with the planet mass, accounting for ~1.3, 7, 20, and $40 \times 10^{-3} M_{\text{Jupiter}}$ for the 1, 3, 5, and 10 Jupiter-mass planets, respectively. The entire Hill spheres contained less than three times more mass in all cases. The CPD masses are lower than the few Jupiter-mass planets, but they are at least an order of magnitude higher than locally isothermal simulations found in the past (D’Angelo et al. 2003; Gressel et al. 2013; Szulágyi et al. 2014). Therefore, the inclusion of thermal processes in the hydrodynamic simulations is important to unveil the basic characteristics of the subdisk. The disk mass not only scales with the possible mass, density, temperature, and kinematic properties. Second, the characteristics of the subdisk are also constrained where and when the satellites can form in these disks. 

Figure 19. Circumplanetary disk (left panel) and Hill-sphere masses (right panel) as a function of planetary mass. The CPD mass depends as strongly on the circumstellar disk mass as on the planetary mass. For the fitted functions see Equations (6), (7).

Regarding the kinematic properties of the circumplanetary gas, the envelope cases ($T_p = 10,000$ K, 8000 K, and 6000 K simulations for the $1 M_{\text{Jupiter}}$) have slow rotation and are mostly characterized by convection in the inner parts. As the planetary temperature drops, the rotation enhances, as does the vertical influx speed (peaking at $13 \text{ km s}^{-1}$ for $T_p = 1000$ K). For the 3–10 $M_{\text{Jupiter}}$, these velocities are even higher because of the higher planetary mass. For lower planetary temperatures, the vertical influx velocity peaks at higher than 25 km s$^{-1}$ for the high-mass planet simulations. This is a very high vertical velocity with respect to the other parts of the CSD and the gap, which makes it possible to aim for a detection of the subdisk based on its kinematic contrast with the surrounding protoplanetary disk.

Because our simulations contain an entire protoplanetary disk, the planetary gap structure was examined as well. We found that the gap is deeper and wider as the planet radiates away its formation heat, but this effect is relatively small in comparison to other effects (such as the change in viscosity). We also showed that the gap has a 3D structure and its profile changes with the vertical distance from the planet, therefore 3D gaps do differ from 2D simulation gaps. Moreover, we confirmed the findings of Kley & Dirksen (2006) that for high-mass planets ($\gtrsim 5 M_{\text{Jupiter}}$) the gap eccentricity increases, hence the CSD regularly engulfs and then truncates the subdisk, creating an environment that is too violent for satellites to form. With the growing gap eccentricity, the CPD becomes more elongated.

To provide more in-depth observational constraints and to create synthetic images for observations from these simulations, a wavelength-dependent radiative transfer software needs to be applied to the hydrodynamic fields. This will be part of a future work.
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