Hydrogen Recombination Line Luminosities and Variability from Forming Planets

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Abstract

We calculated hydrogen recombination line luminosities (H-α, Paschen-β and Brackett-γ) from 3D thermohydrodynamical simulations of forming planets from 1 to 10 Jupiter mass (M_{Jup}). We explored various opacities to estimate the line emissions with extinction, in each case assuming boundary-layer accretion. When realistic opacities are considered, only lines from planets \( \geq 10 M_{\text{Jup}} \) can be detected with current instrumentation, highlighting that most planets do not have detectable emission. This might explain the very low detection rate of H-α from forming planets from observations. While the line emission comes from both the forming planet and its circumplanetary disk, we found that only the disk component could be detected due to extinction. We examined the line variability as well, and found that it is higher for higher-mass planets. Furthermore, we determine for the first time the parametric relationship between the mass of the planet and the luminosity of the hydrogen recombination lines, as well as the equation between the accretion luminosity and hydrogen recombination line luminosities.

Unified Astronomy Thesaurus concepts: Exoplanet detection methods (489); Accretion (14); Photoionization (2060); Extrasolar gas giants (509); Protoplanetary disks (1300)

1. Introduction

Hydrogen recombination lines are traditionally used in the astrophysics community to estimate accretion rates. Similar to young stars, forming planets are also believed to emit hydrogen recombination lines; however it is still unclear what planetary masses can indeed cause detectable hydrogen ionization. Two processes possibly cause hydrogen ionization: (i) thermal ionization occurring for gas temperatures above \( \sim 10,000 \) K, and (ii) collisional ionization, which requires an accretion flow fast enough to produce ionized hydrogen. Whether these conditions are present for planetary-mass objects, which are cooler than stars, is the subject of current investigations (Ayliffe & Bate 2009a, 2009b; Szulágyi 2017). The first detection of an accreting planet via the H-α tracer in the circumstellar disk (CSD) was in the system LkCa15 (Sallum et al. 2015). However, follow-up observations of this source by independent groups were unable to detect the H-α signal again (Mendigutía et al. 2018). More recently, H-α was detected from the planetary candidate PDS 70b, with an estimated accretion rate of \( 10^{-8} M_{\text{Jup}}/\text{yr}^{-1} \) (Wagner et al. 2018). The detection of H-α from PDS 70b was confirmed in 2019 and, additionally, another planetlike H-α source was found in the system (Haffert et al. 2019). It is puzzling, however, that despite the effort of ongoing surveys (Cugno et al. 2019; Zurlo et al. 2020) to detect forming planets via H-α, until now planetlike H-α detections have only been obtained for the above two circumstellar disks. In the Zurlo et al. (2020) survey the authors could close out an accretion luminosity of \( 10^{-6} L_\odot \) at a separation of 0.\,\,′/2 from the host star. In Cugno et al. (2019) the upper limit for H-α fluxes was around \( 10^{-14} - 10^{-15} \text{erg s}^{-1} \text{cm}^{-2} \) for the different systems. Given that H-α is generally a robust tracer of accretion, the question then arises as to why there are so few detections of this line from forming planets. One problem may be the extinction. The forming planet is surrounded by a circumplanetary disk (Kley 1999; Lubow et al. 1999), which may absorb most of the hydrogen recombination lines emitted by the accreting planets (Szulágyi et al. 2019). At medium to large inclinations, the circumstellar disk can also absorb out a significant fraction of the H-α flux. Until now this complex 3D problem has prevented the magnitude of the extinction from being robustly estimated. The second problem is clearly that planets are not as hot as stars, and even the accretion flow to the forming planet cannot always heat up the gas and ionize it. It is important to understand what is the temperature on the surface of the forming planet and in the circumplanetary disk in order to investigate whether and where hydrogen ionization can occur. The third possible reason why there have not been many H-α detections from forming planets is the potential variability of this line. As planets orbit in circumstellar disks, their accretion rate and the extinction rate change, presumably causing variations in the hydrogen recombination line luminosities. The magnitude of the possible line variability is currently unknown.

The first rough estimates of H-α luminosities from 3D thermohydrodynamical simulations of forming planets and their circumplanetary disks used the T Tauri empirical formula (Rigliaco et al. 2012) that connects \( L_{\text{acc}} \) to \( L_{\text{Hα}} \) (Szulágyi & Mordasini 2017). These models ignored extinction and suggested that all examined planetary masses (1, 3, 5, 10 \( M_{\text{Jup}} \)) might emit of the order of \( 4-7 \times 10^{-6} L_{\odot} \) in \( L_{\text{Hα}} \) (Szulágyi & Mordasini 2017). This result is in strong contrast to the low detection rate of H-α from observational surveys. Part of the discrepancy may arise from the fact that the accretion process around planets could be significantly different from that of stars, rendering the T Tauri empirical formula inadequate in this case. Indeed, while stars have strong magnetic fields that lead to magnetospheric accretion, planets are expected to have much weaker fields (at least today they have field strengths that are approximately three orders of magnitude smaller), which in many cases are not strong enough to support magnetospheric accretion. It is suspected that planets may instead grow via boundary-layer accretion, when the circumplanetary disk directly touches the planet surface.
Figure 1. Meridional circulation (from Szulágyi et al. 2014) between the circumstellar and circumplanetary disk (orange “butterfly-pattern” in the center of the image) schematized on a 2D vertical surface for simplicity. Gas from the higher-density regions enters the lower-density gap regions, then spirals down to the CPD. The nonaccreted gas is then pushed back inside the CPD midplane regions to the circumstellar disk. It rises up again there to maintain the vertical hydrostatic equilibrium and to maintain the flow. This continuous material feeding from the circumstellar disk assures that the CPD density scales with the CSD density (Szulágyi 2017). Streamlines video are available at https://www.ics.uzh.ch/~judits/images/visu/video_6.mp4.

Figure 2. Zoom into the circumplanetary disk in the 10 $M_{\text{Jup}}$ simulation, with a few representative streamlines of the gas to show the flow direction. Some of the streamlines accrete directly onto the planet, while others, farther away from the planet in the $x$-direction, land onto the circumplanetary disk, and leave it in the midplane regions to flow back to the circumstellar disk, thus maintaining meridional circulation (Szulágyi et al. 2014; Fung & Chiang 2016).
which is why we used this assumption. However, there is no clear consensus about which way forming planets accrete, due to a lack of adequate magnetohydrodynamic simulations of forming planets.

One important result from 3D simulations is that the accretion shock front is located on the circumplanetary disk (Tanigawa et al. 2012; Szulágyi & Mordasini 2017) rather than being on the planetary surface, as suggested by 1D simulations (Marleau et al. 2019). Indeed 3D simulations show that the accretion stream is launched from the upper layers of the circumstellar disk, spiraling down to the circumplanetary disk through the so-called meridional circulation (Figure 1; Szulágyi et al. 2014; Fung & Chiang 2016, whose findings have now been observed: Teague et al. 2019) and hitting its surface, while creating a luminous shock front on it (Figures 1, 2). This shock can be hot enough to ionize hydrogen (Figures 3, 4), thus H-\(\alpha\) emission could be expected to arise from both the planet and the circumplanetary disk. Aoyama et al. (2018) carried out detailed 1D analytical calculations in order to estimate the hydrogen recombination line fluxes under the assumption that the lines are emitted from the surface of forming planets. These calculations found that forming planets can indeed produce all the hydrogen recombination lines with very high line luminosities, again in tension with current observational results. This result was mainly driven by an assumption of extremely high temperatures (approximately \(10^{4}\)–\(10^{5}\) Kelvin on the surface of planets) and high collisional velocities (>20 km s\(^{-1}\)), which are not expected on the surfaces of forming planets (Szulágyi 2017), but could be perhaps more appropriate for stars.

Figure 3. Temperature map of the circumplanetary disk in the 10 \(M_{\oplus}\) simulation (i.e., the hottest simulation). As mass flows in with high velocities (few streamlines shown), it creates a hot shock front onto the surface of the circumplanetary disk (dark orange surface above and below the planet). In this figure the circumplanetary disk is clearly visible in orange, showing that the disk is hotter than its surroundings.

Figure 4. Left: temperature-map zoom into the planet vicinity for the 10 \(M_{\oplus}\) simulation (i.e., the hottest case). The shock front on the circumplanetary disk above the planet is clearly visible, with high temperatures. This is the region that is hot enough to ionize hydrogen. Middle: density color map of the same region. Right: ionization fractions in the same region. Clearly, ionization, and therefore hydrogen recombination line production, happens in the planet and in the circumplanetary shock front. The planet’s contribution to the line luminosity, however, is obscured by the upper layers of the circumplanetary disk, meaning that only the line emission from the circumplanetary disk can be observable.
In this work we have self-consistently calculated hydrogen recombination line emissions from 3D thermohydrodynamical models of forming planets, including extinction. We examined the expected line variability for H-α, Paschen-β, and Brackett-γ lines and for the first time determined the parametric equation between the accretion luminosity $L_{\text{acc}}$ and the hydrogen recombination line fluxes for planets.

2. Methods

2.1. Hydrodynamical Simulations

We have used 3D thermohydrodynamical simulations performed with the JUPITER code (Szulágyi et al. 2016). This algorithm, developed by F. Masset and J. Szulágyi, solves the Euler equations, and calculates the temperature via a radiative module using a flux-limited approximation (see e.g., on Figure 3; Kley 1989; Commerçon et al. 2011). The heating and cooling channels include viscous heating, shock heating, adiabatic compression (e.g., due to accretion onto the planet), adiabatic expansion, and radiative dissipation.

The simulations are the same as those in Szulágyi & Mordasini (2017) and consist of a circumstellar disk (Figure 5) forming one planet of a given mass. The coordinate system is spherical and centered on the 1 $M_\odot$ star, that was treated as a point mass. The ring of the circumstellar disk around the star spans a distance between 2.0 and 12.4 au (sampled over 215 cells), and the planet is placed at 5.2 au (Jupiter’s distance from the Sun). The circumstellar disks initial surface density is set as $\Sigma = \Sigma_0 (r/5.2au)^{-0.5}$, with $\Sigma_0 = 222.2$ g cm$^{-2}$. This makes the total disk mass approximately 11 $M_{\text{Jup}}$, which is an average protoplanetary disk mass from observations (Williams & Cieza 2011). A power-law slope of $-0.5$ is again chosen based on observational constraints (Andrews et al. 2009; Isella et al. 2009). In different simulations we study planets of different masses, namely 1, 3, 5, and 10 $M_{\text{Jup}}$. These are treated as a point mass in the corners of the eight cells. The planet is thus unresolved and represented by a gravitational potential well. However, a small gravitational softening$^4$ is used in order to avoid a singularity, with smoothing lengths of $6.5 \times 10^{10}$, $1.3 \times 10^{11}$, and $2.7 \times 10^{11}$ cm for the 1, 3, 5, and 10 $M_{\text{Jup}}$ planets, respectively. Nested meshes are used in the JUPITER code in order to increase the resolution near the planet. With each level of refinement, the resolution doubles and we use six levels of refinement to approach a length compared to Jupiter’s radius, with the smallest cells being $1.1 \times 10^{10}$ cm, i.e., ~0.8 Jupiter diameter. The opening angle of the circumstellar disk is 7°4 (using 20 cells resolution on the base mesh). The circumstellar disk is resolved with 680 cells to cover the $2\pi$ azimuthal extension. We employ the ideal gas equation of state with a fixed adiabatic index of 1.4 and a mean molecular weight of 2.3 (corresponding to the solar value). The fixed adiabatic index is a limitation, as in reality it would change due to molecular hydrogen dissociation and ionization. A constant kinematic viscosity with a value of $10^{15}$ cm$^2$ s$^{-1}$ is used. The opacity table used in the hydrodynamic simulations is a frequency-independent Rosseland-mean-opacity (Bell & Lin 1994). Our simulations do not contain magnetic fields, hence they are valid only for boundary-layer accretion, rather than for magnetospheric accretion.

2.2. Line-luminosity Calculation

We postprocessed the temperature and density fields from the hydrodynamic simulations in order to calculate an ionization rate via the Saha equation (Saha 1920) and used this to derive the electron number densities. We obtained the hydrogen number densities from the total gas densities assuming a mean molecular weight of 2.3, consistent with the hydrodynamic simulations. The hydrogen recombination spectrum was then calculated by applying the formalism used in the MOCASSIN code (Ercolano et al. 2003, 2005, 2008) and based on the detailed atomic data calculations of Storey and Hummer (1995). We obtained the emerging line intensities of Hα (0.6563 μm), Paschen-β (1.2818 μm), and Brackett-γ (2.165 μm) by integrating the local line luminosities from the midplane of the disk to the surface, assuming the disk to be face-on (best case scenario) and including extinction along the line of sight, i.e., absorption due to the gas and the dust grains in the disk. The size distribution and the chemical composition of the dust grains in the disks are unfortunately poorly known and these can strongly affect the opacities. In order to assess the uncertainties introduced by the unknown grain properties, we experimented with four very different opacity tables:

1. Dust mixture of 40% silicates +40% water-ice +20% carbon (i.e., graphite), with dust grain sizes of 1 micron, and a dust-to-gas ratio of 1% (Zubko et al. 1996; Draine 2003; Warren & Brandt 2008).

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$^4$ Gravitational softening means that within the smoothing radius ($r_s$) the planet’s gravitational potential ($U_p$) is artificially lowered. The equation used is $U_p = -\frac{GM_p}{\sqrt{x^2 + y^2 + z^2 + r_s^2}}$. 
2. Silicate grains, with a size distribution between 0.005 microns and 2.5 microns (with a slope of $-3.5$), and a dust-to-gas ratio of 1% (Mathis et al. 1977; Draine & Lee 1984).

3. Graphite grains, with a dust grain size distribution between 0.005 microns and 2.5 microns (with a slope of $-3.5$), and a dust-to-gas ratio of 1% (Mathis et al. 1977; Draine 2003).

4. Only gas opacities (Draine 2003), describing a case where the dust has sublimated or the disk is otherwise depleted from dust.

The gas-only case gives an absolute upper limit (theoretical limit) for the line luminosities, since the presence of dust in protoplanetary disks is well established from observations. The graphite (i.e., carbon) grains have a very high opacity, and considering only them is a limit of the highest possible opacity case (i.e., minimal line luminosities). A realistic disk might have a composition similar to our silicate-water-carbon case.

Finally, we estimated the variability of the lines. The main reasons for variability are the changes in extinction and changes in the accretion rate. In the hydrodynamic simulation there are changes in the CPD accretion rate from the meridional circulation as the planet orbits around the star. This leads to changes in the strength/temperature of the shock front on the circumplanetary disk (Figure 3). Similarly, due to the orbit around the star, and the CPD rotation around the planet, the extinction column changes rapidly (see more in Section 3.2).

3. Results

3.1. The Line Luminosities

The computed line luminosities in Solar-luminosity units ($L_\odot$) can be found in Table 1. We tested what percentage of the line luminosities come from the circumplanetary disk only, by removing the planet entirely from the integration for the line emissivities. This calculation showed that 100% of the reported luminosities come from the circumplanetary disk only, by removing the planet entirely from the integration for the line emissivities. This calculation showed that 100% of the reported luminosities come from the circumplanetary disk itself in our boundary-layer accretion assumption. If the planet has strong magnetic fields, this could lead to a cavity between the planet surface and the CPD, which would help the planet-generated hydrogen recombination lines to escape. Therefore, in the boundary-layer accretion assumption, the observability of hydrogen lines from forming planets can only be estimated via modeling of the circumplanetary disk rather than the planet interior and surface.

With the most realistic disk opacities (the silicate-water-carbon mixture), only the 10 $M_{\text{Jup}}$ case could be robustly observed with luminosities peaking at approximately few times $10^{-2} L_\odot$ for H-$\alpha$ and for Paschen-$\beta$ and approximately few times $10^{-3} L_\odot$ for the Brackett-$\gamma$ lines. For the 5 $M_{\text{Jup}}$ case due to the line variability, sometimes the hydrogen recombination line luminosities are on the detection limit, with values between $\sim 10^{-8}$ and $10^{-5} L_\odot$. We emphasize, however, these calculations assume the most favorable configuration (face-on disk, local thermal equilibrium approximation), and should thus be considered upper limits. For the lower-mass planet cases ($\leq 3$ $M_{\text{Jup}}$), with this opacity table the line luminosities are always $<10^{-11} L_\odot$ for all lines, well below the detection limits of current instruments. This might explain why so few detections of H-$\alpha$ from planetary-mass objects exist, given that planets above 5 $M_{\text{Jup}}$ are rare.

For comparison purposes, we have also calculated the line luminosities with pure silicate opacities only. As silicate has a lower opacity than carbon and water, these line fluxes are higher than the mixture case containing those two (Table 1). For the 3 and 5 $M_{\text{Jup}}$ cases the line luminosities usually range between $10^{-4} L_\odot$ and $10^{-9} L_\odot$, which could be observable with current instruments in favorable conditions. The 10 $M_{\text{Jup}}$ planet produces between $10^{-3}$ and $10^{-2} L_\odot$ for Paschen-$\beta$ and Brackett-$\gamma$ lines and up to $10^{-4} L_\odot$ for H-$\alpha$. Using the graphite (i.e., carbon) opacity, the line luminosities are more extinct than those in the pure silicate case. Still, the 5 $M_{\text{Jup}}$ cases could be near the observable limits for all lines (Table 1). All the hydrogen recombination lines are easily observable from the 10 $M_{\text{Jup}}$ planet simulations, however, the 1–3 $M_{\text{Jup}}$ cases are below the detection limit.

Considering only gas opacities (i.e., almost no extinction), all the lines for all planetary masses considered here could be observable with line fluxes larger than $10^{-6} L_\odot$. This case might be relevant only if all dust grains have sublimated or in the unlikely case of circumplanetary disks that are intrinsically free of dust (Zhu 2015). These line fluxes obtained under the no dust assumption, therefore, should considered theoretical upper limits. More likely, dust extinction in the circumplanetary disk (Dražkowska & Szulágyi 2018) and its atmosphere will reduce the line luminosities by several orders of magnitude (see Table 1).

Our results suggest that when realistic opacities are considered (mixture of silicate, water, and carbon), detecting forming planets smaller than 10 $M_{\text{Jup}}$ via hydrogen recombination lines is challenging with current instrumentation. Forming planets larger than this limit might be observable, but unfortunately their occurrence rate is relatively low. As well as intrinsically brighter line luminosities, the observability of 10 $M_{\text{Jup}}$ forming planets is higher due to the planet carving a deeper gap in the circumstellar disk, which results in lower extinction above the circumplanetary disk shock surface. In the lower-planetary-mass cases, the gap is shallower and less empty, hence extinction more severely affects the line luminosities. The situation is of course more complex when the system is inclined from the line of sight, since in this case additional line absorption from circumstellar disk material can then be expected as well.

3.2. Variability

The line variability was also examined. As mentioned before, the accretion rate onto the CPD and thus the shock-front strength will change as the planet orbits the star. Even more importantly, the density around the planet & CPD also changes during the orbit, leading to different extinction columns at different times. For these reasons, we considered four different points during the orbit of the planet, whenever such simulation outputs were available (for the 3, 5, 10 $M_{\text{Jup}}$ simulations). We calculated the line variability using the data from Table 1, excluding the non-detections (defined by $<10^{-22} L_\odot$). The standard deviations of the four values in each cases were divided with the maximal line luminosity, and expressed in percentages (Table 2). We used the maximal line luminosity in each case instead of the average, because due to the often low luminosity values, the maximums are more robust than the averages.

5 http://exoplanet.eu/
### Table 1

Line Luminosities in Solar-luminosity \([L_\odot]\) Units for Each Planetary Mass, and Four Different Opacity Tables (Indicated in the Brackets in the First Column)

| Mass in \(L_\odot\) | \(1 \, M_{\text{Jup}}\) | \(3 \, M_{\text{Jup}}\) | \(5 \, M_{\text{Jup}}\) | \(10 \, M_{\text{Jup}}\) |
|----------------------|----------------|----------------|----------------|----------------|
| \(L_{\text{H}}\) (mix) | 0.00E+00 | 1.09E-24 | 1.82E-22 | 6.11E-11 |
| \(L_{\text{Br}}\) (mix) | 0.00E+00 | 2.93E-27 | 5.97E-25 | 9.46E-08 |
| \(L_{\text{Pa}}\) (mix) | 0.00E+00 | 1.61E-25 | 2.40E-23 | 4.90E-07 |
| \(L_{\text{H}}\) (silicate) | 0.00E+00 | 2.62E-09 | 8.28E-09 | 2.63E-04 |
| \(L_{\text{Br}}\) (silicate) | 2.32E-11 | 1.13E-06 | 2.05E-06 | 7.77E-05 |
| \(L_{\text{Pa}}\) (silicate) | 2.21E-23 | 7.60E-07 | 1.38E-07 | 2.12E-06 |
| \(L_{\text{H}}\) (graphite) | 0.00E+00 | 8.94E-20 | 3.75E-18 | 4.93E-08 |
| \(L_{\text{Br}}\) (graphite) | 0.00E+00 | 7.47E-10 | 1.92E-09 | 7.33E-06 |
| \(L_{\text{Pa}}\) (graphite) | 0.00E+00 | 2.37E-13 | 1.38E-12 | 9.96E-10 |
| \(L_{\text{H}}\) (gas) | 7.95E-05 | 1.89E-04 | 4.85E-04 | 9.68E-04 |
| \(L_{\text{Br}}\) (gas) | 1.64E-06 | 3.08E-06 | 8.13E-06 | 2.95E-04 |
| \(L_{\text{Pa}}\) (gas) | 6.24E-06 | 1.29E-05 | 3.37E-05 | 3.74E-05 |

**Note.** The four values given for the 3–10 \(M_{\text{Jup}}\) measured at four points of the orbit of the planet around the star, to examine line variability. The last row is the mass influx rate to the CPD, highlighting the changes in this value, which also contribute to the line variability, apart from changes in the extinction column.
In most cases, the variability is between 28% and 58% (Table 2). These are slightly higher values than the corresponding variability of the mass influx to the CPD. The variabilities of the influx are 18.9%, 12.4%, and 19.1% for the 3, 5, and 10 $M_{\text{Jup}}$ cases, respectively. This highlights that the variability is partially due to the mass influx rate to the CPD (and hence the varied shock-front strengths) and also the changes in the extinction column. Furthermore, the effect of variable extinction can be seen by the lower line variability in the gas-only cases in Table 2 relative to the dust-included opacity cases. The high variability of these lines can be a further explanation why in the case of the LkCa 15b planet candidate, H-$\alpha$ could be detected in one observation (Sallum et al. 2015), but not in others (Mendigutía et al. 2018); it is indeed possible that the H-$\alpha$ production at the time of the second observation was just below the observational limit.

### 3.3. The Relation between $M_{\text{planet}}$ and $L_{\text{H\alpha}}$

In general, line luminosities increase with increasing planetary mass (Table 1). We calculated the regression between each line versus the planetary mass, to obtain a rough $M_{\text{planet}} \propto \log_{10}(L_{\text{line}})$ relationship. We used the data from Table 1, excluding the nondetection cases when calculating the regression. The coefficients of the fitted lines can be found in Table 3 for each opacity case separately. The trend of increasing line luminosity with increasing planetary mass is on one hand driven by the temperature being generally higher in the vicinity of a more massive planet, resulting in more hydrogen ionization and hence higher line luminosities. Furthermore, the extinction column also decreases with increasing planetary mass: the larger-mass planets open deeper gaps, and the atmosphere region of the CPD is thinner (while the CPD density is overall higher) than in the low-planet-mass cases. We also found that all of the observable hydrogen recombination line production comes from the circumplanetary disk shock, rather than from the planet itself. An observer might see this luminous shock front, while the planet emissivity would be absorbed by the large extinction in the circumplanetary disk (Figure 4).

### 3.4. The Relation between $L_{\text{acc}}$ and $L_{\text{H\alpha}}$

As mentioned above, an empirical relation between accretion luminosity ($L_{\text{acc}}$) and the hydrogen recombination line luminosity ($L_{\text{H\alpha}}$) has been derived from observations of young T Tauri stars (Rigliaco et al. 2012; Alcalá et al. 2014). However, the validity of this relationship for planets is questionable. In what follows we determine the relationship between $L_{\text{acc}}$ and $L_{\text{H\alpha}}$ based on our simulations. First, we obtained the mass influx rate to the circumplanetary disk (Tanigawa et al. 2012; Szulágyi et al. 2014) $A = \rho s v_{\text{z}}$, where $\rho$ stands for density, $s$ for surface, and $v_{\text{z}}$ for the z-component of velocity) that generates the shock front (see the last row in Table 1). This is not the actual accretion (i.e., net growing) rate of the circumplanetary disk, or of the planet, because most of this mass (>90%) will be recycled and will flow back to the midplane regions of the circumplanetary disk (Figures 1, 2). The accretion luminosity can be computed from the mass fluxes using the formula $L_{\text{acc}} = GM_{\text{planet}}A/R$, where $G$ is the gravitational constant, $A$ is the mass influx rate, and $R$ is the distance of the surface where the mass influx was computed. We used $R = 4 \times 10^{11}$ cm, which is just above the shock front in these simulations. As a next step, we computed the regression between $\log_{10}(L_{\text{acc}})$ and $\log_{10}(L_{\text{H\alpha}})$ from Table 1, excluding the nondetection cases. The fitted line values and uncertainties are given in Table 4. Here, the slope seems to be steeper for planets than in the case of stars (slope $\approx 1$ Rigliaco et al. 2012; Alcalá et al. 2014), suggesting that the accretion process might indeed be different for planets and for stars. However, this is not surprising since we have assumed boundary-layer accretion in our calculations. It remains to be seen whether calculations including magnetospheric accretion might retrieve slopes closer to the T Tauri values. In any case, our values also indicate that in the case of boundary-layer accretion, previous observations and analyses that employed the T Tauri formula for forming planets might have

### Table 2
Variability of the Lines (in Percentages) for the Four Different Opacity Tables and the Various Planetary Masses

| 3 $M_{\text{Jup}}$ [%] | 5 $M_{\text{Jup}}$ [%] | 10 $M_{\text{Jup}}$ [%] |
|-------------------------|------------------------|-------------------------|
| $\Delta_{\text{Br}}$ (mix) | 57.7                  | 47.7                    | 34.6                    |
| $\Delta_{\text{Br}}$ (silicate) | 49.9                  | 49.0                    | 30.1                    |
| $\Delta_{\text{Br}}$ (graphite) | 20.9                  | 37.8                    | 29.0                    |
| $\Delta_{\text{Br}}$ (gas) | 41.5                  | 46.9                    | 29.6                    |
| $\Delta_{\text{H}}$ (silicate) | 57.7                  | 48.3                    | 33.5                    |
| $\Delta_{\text{H}}$ (graphite) | 49.1                  | 49.0                    | 29.6                    |
| $\Delta_{\text{H}}$ (gas) | 50.0                  | 49.0                    | 32.0                    |
| $\Delta_{\text{H}}$ (gas) | 33.2                  | 28.3                    | 28.4                    |
| $\Delta_{\text{H}}$ (gas) | 34.0                  | 28.5                    | 29.0                    |
| $\Delta_{\text{H}}$ (gas) | 33.7                  | 29.0                    | 29.3                    |

### Table 3
Planet Mass vs. Hydrogen Recombination Line Luminosities

| $L_{\text{H\alpha}}$ (opacity table) | $a$ | $b$ | $\sigma$ |
|-------------------------------------|-----|-----|----------|
| $L_{\text{H\alpha}}$ (mix) | 2.23 | -22.76 | 0.53     |
| $L_{\text{H\alpha}}$ (mix) | 2.29 | -21.56 | 0.55     |
| $L_{\text{H\alpha}}$ (mix) | 2.22 | -23.69 | 0.52     |
| $L_{\text{H\alpha}}$ (sil.) | 1.09 | -11.31 | 0.24     |
| $L_{\text{H\alpha}}$ (sil.) | 0.55 | -7.80  | 0.11     |
| $L_{\text{H\alpha}}$ (sil.) | 1.12 | -11.75 | 0.37     |
| $L_{\text{H\alpha}}$ (graph.) | 1.81 | -18.68 | 0.40     |
| $L_{\text{H\alpha}}$ (graph.) | 0.89 | -11.52 | 0.18     |
| $L_{\text{H\alpha}}$ (graph.) | 1.52 | -16.67 | 0.40     |
| $L_{\text{H\alpha}}$ (gas) | 0.35 | -4.26  | 0.04     |
| $L_{\text{H\alpha}}$ (gas) | 0.34 | -5.99  | 0.05     |
| $L_{\text{H\alpha}}$ (gas) | 0.36 | -5.43  | 0.04     |

Note. Coefficients for regression for the $\log_{10}(L_{\text{H\alpha}}) = a M_{\text{planet}} + b$ relation and the $1\sigma$ uncertainty estimates for the parameter “$a$”. The four different opacity tables considered are indicated in parentheses in column one.
overestimated the accretion rates of the planets (or rather, of the circumplanetary disks).

4. Discussion

These simulations do not contain magnetic fields; however, the circumplanetary disk magnetic field could change the accretion rate to the planet (Gressel et al. 2013). If the planet has strong magnetic fields (≥65 Gauss, according to Owen & Menou 2016), it can accrete via magnetospheric accretion like stars do, instead of boundary-layer accretion (Batygin 2018). Due to a lack of simulations on the topic, it is unknown what field strength forming planets might have and whether they accrete via boundary-layer accretion or magnetospheric accretion. It could also very well be that this is not a “this or that” question, and some planets would accrete one way and others another way. Furthermore, the magnetic field of the planet is expected to change during its evolution, as is the case for stars (Christensen et al. 2009). Clearly, magnetospheric accretion would completely change the accretion flow and rate in comparison to what this work’s simulations show. In any case, for magnetospheric accretion to happen, two conditions need to be met: first, the planet should have a strong (≥65 Gauss, Owen & Menou 2016) field; second, there should be a sufficient amount of ionized gas in the CPD. Regarding the first condition, today Jupiter has a 5 Gauss field. It could be the case that planets during their formation had larger magnetic fields, which is true for stars (Christensen et al. 2009). Owen & Menou’s (2016) back-of-an-envelope estimation suggested that Jupiter might have had a ~50 Gauss field during its infancy, but this would still not be enough to launch magnetospheric accretion. Regarding the ionization rates, the bulk of the CPD is neutral (see, e.g., Figure 4; Fujii et al. 2011, 2014). However, Batygin (2018) calculated from our models that alkali elements might have enough ionization. In any case, full 3D magnetohydrodynamic simulations are needed with planet magnetic fields included, in order to understand how the accretion stream changes in the magnetospheric accretion case. So far no such simulation has been possible due to the limitations of modern computers. Furthermore, dynamo models are needed for forming planets to understand what field strength we can expect at this stage (that is still completely unknown). It is likely that our parametric equation slope value differs from that of stars, because of our assumption of boundary-layer accretion. The parametric equations would likely be different for magnetospherically accreting planets.

In this work we also omitted gas self-gravity, which could play an important role in the runaway phase (Pollack et al. 1996; Piso et al. 2015). The inclusion of self-gravity would help with the CPD-collapse and presumably increase the accretion rate (Ayliffe & Bate 2012). However, running 3D global simulations with radiation transport, as well as with planet resolution in the Hill sphere, together with self-gravity, would be computationally very expensive and could be done only on next-generation computers.

The accretion rates of planets and CPDs are known to depend on the circumstellar disk surface density, the viscosity assumed, and the scale height of the circumstellar disk (e.g., the semimajor axis of the planet and the temperature of the CSD). These effects therefore can also somewhat affect the calculated line fluxes, (in particular, a different density will lead to a different extinction rate. Due to the expensiveness of these high-resolution simulations with all the physics mentioned in Section 2.1 included (approximately 1.2 × 10^4 core-hours per simulation), it is only possible to explore a small part of the parameter space.

Our simulations had a resolution somewhat smaller than the radius of forming planets (∼~0.8 Jupiter diameter), and we did not include any planet interior models. Such models could potentially better estimate the hydrogen recombination line emission from the forming planets. The emission of the interior, however, necessarily will be absorbed by the inner and outer regions of the planet. Only the atmosphere production would be able to leave the planet, but then—which happens in our simulations as well—it will likely be absorbed by the CPD material.

5. Conclusion

In this work we computed self-consistently H-α, Paschen-β, and Brackett-γ line luminosities from 3D thermodynamical simulations with JUPITER (Szulágyi et al. 2016). The planet masses considered were 1, 3, 5, and 10 M_Jup. Line luminosities from recombination cascades were estimated using the formalism in the MOCASSIN code (Ercolano et al. 2003, 2005, 2008) in combination with a ionization calculation using the Saha equation. We explored various opacities to estimate the line emissions with extinction in each case. In the most realistic opacity case (dust mixture of 40% silicates + 40% water-ice + 20% carbon) only planets ≥10 M_Jup can be detected with current instrumentation. The detectable line flux originated in all cases from the CPD surface shock front, while the planet-emitted contributions were completely absorbed. Our results indicate that detecting hydrogen recombination lines from forming planet is very challenging with current instrumentation, which might explain the very few detections reported so far.

Our study on line flux variability showed a change of 28%—58%, mainly due to changes in extinction (changes in density) as the planet orbits around the star and the CPD rotates around the planet. Second, the changes in the mass influx to the CPD along the orbit also change the strength of the accretion shock, which translates into different line luminosities.
We determined for the first time the parametric equation between the accretion luminosity and the H recombination line luminosity for planets. Moreover, we also determined the relationship between the planetary mass and the line luminosities for H-α, Paschen-β, and Brackett-γ separately, as well as the planetary mass and line luminosities for various opacity cases. These relationships for planets seem to be steeper than the equations for T Tauri stars, with our boundary-layer accretion assumption. Future magnetohydrodynamic simulations are needed in the CPD region to examine a potential magnetospheric accretion if the planet magnetic fields are very high (>65 Gauss; Owen & Menou 2016).

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References
Alcalá, J. M., Natta, A., Manara, C. F., et al. 2014, A&A, 561, A2
Andrews, S. M., Wilner, D. J., Hughes, A. M., Qi, C., & Dullemond, C. P. 2009, ApJ, 700, 1502
Aoyama, Y., Ikoma, M., & Tanigawa, T. 2018, ApJ, 866, 84
Ayliffe, B. A., & Bate, M. R. 2009a, MNRAS, 393, 49
Ayliffe, B. A., & Bate, M. R. 2009b, MNRAS, 397, 657
Ayliffe, B. A., & Bate, M. R. 2012, MNRAS, 427, 2597
Batygin, K. 2018, AJ, 155, 175
Bell, K. R., & Lin, D. N. C. 1994, ApJ, 427, 987
Christensen, U. R., Holzwarth, V., & Reiners, A. 2009, Natur, 457, 167
Commerçon, B., Teysier, R., Audid, E., Hennebelle, P., & Chabrier, G. 2011, A&A, 529, A35
Cugno, G., Quanz, S. P., Hunziker, S., et al. 2019, A&A, 622, A156
Draine, B. T. 2003, ApJ, 598, 1026
Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89
Drazkowska, J., & Szulágyi, J. 2018, ApJ, 866, 142
Ercolano, B., Barlow, M. J., & Storey, P. J. 2005, MNRAS, 362, 1038
Ercolano, B., Barlow, M. J., Storey, P. J., & Liu, X.-W. 2003, MNRAS, 340, 1136
Ercolano, B., Young, P. R., Drake, J. J., & Raymond, J. C. 2008, ApJS, 175, 534
Fujii, Y. I., Okuzumi, S., & Inutsuka, S.-i. 2011, ApJ, 743, 53
Fujii, Y. I., Okuzumi, S., Tanigawa, T., & Inutsuka, S.-i. 2014, ApJ, 785, 101
Fung, J., & Chiang, E. 2016, ApJ, 832, 105
Gressel, O., Nelson, R. P., Turner, N. J., & Ziegler, U. 2013, ApJ, 779, 59
Haffert, S. Y., Bohn, A. J., de Boer, J., et al. 2019, NatAs, 3, 749
Isella, A., Carpenter, J. M., & Sargent, A. I. 2009, ApJ, 701, 260
Kley, W. 1989, A&A, 208, 98
Kley, W. 1999, MNRAS, 303, 696
Lubow, S. H., Seibert, M., & Artyomowicz, P. 1999, ApJ, 526, 1001
Marleau, G.-D., Mordasini, C., & Kuiper, R. 2019, ApJ, 881, 144
Mathis, J. S., Rumpl, W., & Nordsieck, K. H. 1977, ApJ, 217, 425
Mendigutia, I., Oudmaijer, R. D., Schneider, P. C., et al. 2018, A&A, 618, L9
Owen, J. E., & Menou, K. 2016, ApJL, 819, L14
Piso, A.-M. A., Youdin, A. N., & Murray-Clay, R. A. 2015, ApJ, 800, 82
Pollack, J. B., Hubickyj, O., Bodenheimer, P., et al. 1996, Icar, 124, 62
Rigliaco, E., Natta, A., Testi, L., et al. 2012, A&A, 548, A56
Saha, M. N. 1920, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 40, 472
Sallum, S., Follette, K. B., Eissner, J. A., et al. 2015, Natur, 527, 342
Szulágyi, J. 2017, ApJ, 842, 103
Szulágyi, J., Dullemond, C. P., Pohl, A., & Quanz, S. P. 2019, MNRAS, 487, 1248
Szulágyi, J., Masset, F., Lega, E., et al. 2016, MNRAS, 460, 2853
Szulágyi, J., Morbidelli, A., Crida, A., & Masset, F. 2014, ApJ, 782, 65
Szulágyi, J., & Mordasini, C. 2017, MNRAS, 465, L64
Tanigawa, T., Ohtsuki, K., & Machida, M. N. 2012, ApJ, 747, 47
Teague, R., Baé, J., & Bergin, E. A. 2019, Natur, 574, 378
Wagner, K., Follette, K. B., Close, L. M., et al. 2018, ApJL, 863, L8
Warren, S. G., & Brandt, R. E. 2008, JGRD, 113, D14220
Williams, J. P., & Cieza, L. A. 2011, ARA&A, 49, 67
Zhu, Z. 2015, ApJ, 799, 16
Zubko, V. G., Mennella, V., Colangeli, L., & Bussoletti, E. 1996, MNRAS, 282, 1321
Zurlo, A., Cugno, G., Montesinos, M., et al. 2020, A&A, 633, A119