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A NEW SCENARIO FOR THE FORMATION OF PLANETARY ATMOSPHERES

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Abstract. The observation of large quantities of CO in many debris disk systems means that we can study its potential impact on the atmospheres of planets embedded in this gas. An analytical model suggests that the accretion of the late gas (>10 Myr) in debris disks onto the planets is really efficient (Kral et al. 2020). In this regard, we are currently developing a code that can confirm this result numerically and determine more precisely the impact of different parameters such as core mass or luminosity on the overall accretion rate in this late phase. Late gas accretion could be one of the missing ingredients in completing (or totally modifying) the atmosphere of terrestrial planets and/or providing volatile substances to giant planets that have already formed.

Keywords: debris disks, exoplanets, atmospheres

1 Introduction

All present models of atmospheric evolution ignore any external source of gas after the evaporation of the protoplanetary disk, which occurs at the very beginning of the system's lifetime (10 Myr at the latest). However, intensive observations have shown that a significant fraction of dusty debris disks, akin to our own asteroid or Kuiper belts made of remnant material that has not been used in the planet-formation process and is collisionally eroding, do host an important amount of gas (Moór et al. 2017), despite being much older than the ∼10 Myr it takes for the primordial gas disk to dissipate. Therefore, the already-formed planets will be bathed in this late gas from the debris disk era for tens or hundreds of Myr, which may affect their atmospheres over long timescales (Kral et al. 2020).

2 Gas in debris disks

2.1 *On the origin of the gas*

As of today, gas has been detected in about 30 debris disks, mostly in the form of CO, but also as atomic species (C, C^+, O), and some more metallic elements (e.g., Fe, Na) that may not have the same origin (grazing exocomets rather than planetesimals at great distances). The estimated CO masses (which usually dominate the total gas mass in debris disks, Cataldi et al. 2023) can be as much as 1 $M_\oplus$ in some cases (Cataldi et al. 2020), but the origin of the gas remains unknown for the most massive systems, especially when considering the fact that CO should be very quickly (< 120 yr, Visser et al. 2009) photodissociated by stellar and interstellar UV radiations. For the least massive systems, the quantities of CO observed are so small that they can be explained as being constantly released from large planetesimals in exo-Kuiper belts but for the most massive gaseous systems, one would have to deplete the whole belt of volatiles at an incredibly unphysical high rate to explain observations. In this case, those gas disks could then not survive for more than a few thousand years and we would not be able to explain their omnipresence around the most luminous debris belts (Moór et al. 2017).

There are basically two competing models to explain these significant quantities of gas around mature stars on the main sequence. One scenario is that these disks are hybrids, meaning that despite having secondary collisionally eroding debris disks, they still contain primordial gas leftover from the protoplanetary disk phase. This would imply that the CO we detect has been shielded from stellar radiation by large amounts of H_2.

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However, a new model, put forward by Kral et al. (2019) and subsequently refined and adapted by Moór et al. (2019), suggests that this gas is actually of secondary origin (similar to the less massive belts) and released from solids in planetesimal belts. In this scenario, hydrogen is not enough to protect carbon monoxide from photodissociation caused by interstellar radiation. However, the gas is shielded by CO itself and the neutral carbon gas produced during CO photodissociation. This model can explain most gaseous debris disks and makes predictions that could be checked in the near future by ALMA observations (e.g. Marino et al. 2020).

2.2 *Accretion onto planets*

Debris disks are, by definition, older than protoplanetary disks, which are the environments in which planets form and whose typical lifetime is only a few million years. This means that, if planets should form in a given system, they are already there by the time the debris disk phase is reached. These planets should have a significant effect on disk morphology (when massive enough) but observing them directly remains challenging due to their faintness and high contrast with the central star. However, a few Jovian planets have been directly imaged in some debris disks at large distances from their host stars (a few to tens of au). In the archetypal β Pic system, for example, two massive planets of roughly 10 and 9 Jupiter masses exist at distances of 9.2 and 2.7 au, respectively (Lagrange et al. 2009, 2019).

For systems in which gas has been detected, this gas should interact with the already formed planets, potentially resulting in gaseous accretion onto the planets, as outlined in Kral et al. (2020). This accretion could be very effective, as the gas produced in the belt spreads viscously towards the planet (Kral & Latter 2016), which in some cases can accrete most of the gas that spreads inwards. It is expected that a gap will form in the gas disk due to the planet's gravitational influence. In this scenario, most of the migrating gas would be stopped at the planet's orbit, so that the radial density profile of the gas disk would end up with a steep inward slope. However, this model has so far been explored with a simplified analytical approach, and it would require validation through more sophisticated numerical simulations. Such sophisticated models would for instance help us quantify the amount of gas that the planet accretes. It would also allow us to estimate important consequences of this gas-accretion phase, notably the effect of the core luminosity. Moreover, we can also explore the impact of some of the disk's key characteristics, such as its density, temperature, and composition, as well as the influence of initial conditions related to the planet, such as core mass and previously accreted atmosphere.

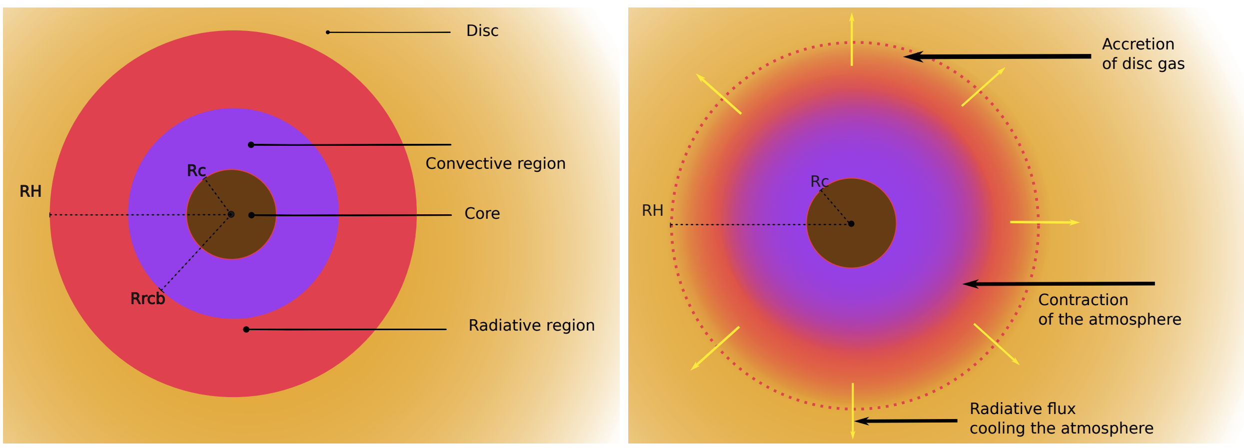

Fig. 1. Left: Structure of the modeled atmosphere and the disk that surrounds it. **Right:** Principle of the gas accretion onto the planet. R_c, R_{rcb}, and R_H are respectively the core radius, the radius at the radiative-convective boundary, and the Hill radius which is our outer integration limit.

3 The numerical model

3.1 *General Principle*

Our code is based on methods developed for gas accretion in protoplanetary disks (e.g. Piso & Youdin 2014, and references therein). Because of the timescale involved (> 100 Myr), we cannot use hydrodynamical simulations.

Similarly to previous work, we will solve the 1D stellar structure equations to handle accretion onto a planet's atmosphere:

$$\begin{cases} \frac{dr}{dm} &= \frac{1}{4\pi r^2 \rho} \\ \frac{dP}{dm} &= \frac{-\mathcal{G}m}{4\pi r^4} \\ \frac{dT}{dm} &= \nabla \frac{T}{P}\frac{dP}{dm} \\ \frac{dL}{dm} &= -T\frac{\partial S}{\partial t}\bigg|_m \end{cases} \tag{3.1}$$

with m, $r(m)$, $P(m)$, $T(m)$, $L(m)$, $S(m)$ the mass, the radius, the pressure, the temperature, the luminosity, and the entropy, respectively (see Figure 1 left to see the structure of the atmospheres we model).

Through the radiative zone, the atmosphere cools down and then contracts. The gas from the disk takes up the space vacated by the contraction and the atmosphere grows and its composition evolves (see Figure 1 right).

In the system of differential equations we have to solve, we have four main parameters: r, P, T, and L. However, we do not have access to their four boundary conditions on the same side of the integration domain. We know the radius and the luminosity at the core $r(M_c) = R_c$, $L(M_c) = L_c$, and the temperature and pressure at the disk boundary: $T(M) = T_D, P(M) = P_D$ with M the total mass and M_c the core mass. Therefore, we use the shooting method to determine the missing parameters and integrate the system (see Figure 2 left).

To integrate the entire problem, we successively solve each spatial snapshot at each time step. The initial spatial state is the adiabatic state, which is time-independent because the adiabatic gradient does not depend on luminosity, so we do not need to solve for the last equation (as it is only the last equation, characterizing the energy transfer, which contains the time dependency). After the initial step, we have to estimate the time derivative of the entropy. To do so, we discretize it in the first order by using the entropy at the previous snapshot. We then have a method to solve the whole problem from the beginning to the end of the disk life ($\sim$ 100 Myr)

3.2 *Adaptation for debris disks*

The gas in debris disks is thought to have a different composition (dominated by CO, C, O) compared to that of protoplanetary disks (dominated by H_2). Moreover, the total gas mass in debris disks is expected to be much smaller than in their younger counterparts. All of this could easily be implemented in the code developed for protoplanetary disks though the timescales of accretion would drastically change. However, in the case of debris disks, we expect from models (e.g. Kral et al. 2019) that the gas release rate from the planetesimal belt is small (at most 1 $M_\oplus$/Myr), and hence the possible accretion rate onto the planets is also smaller than for protoplanetary disks. We end up with the code wanting to accrete more than the total gas that can arrive per unit time, which is a major issue.

We modified the code to handle this matter in the following way. In protoplanetary disks, the density and temperature are fixed at the disk level, and the mass and luminosity are calculated by the shooting method used to solve the set of differential equations above. For debris disks, the temperature at the disk level is fixed and the mass at $t + dt$ is given by the accretion rate τ: $m(t + dt) = m(t) + \tau dt$. The density (instead of mass) and luminosity are now calculated using the shooting method (see Figure 2 right) so that the disk density can decrease if too much gas gets accreted compared to what is refilled. This is more physical and will allow us to make predictions for the 1-D radial profile of gas at the inner boundary of the disk in the presence of different types of planets (and then compare with ALMA observations at high resolution).

3.3 *Work in progress*

We reproduced the result of Piso & Youdin (2014) for protoplanetary disks in order to test the first version of our code. We had to adjust their method because the technique they used to get rid of one of the two boundary parameters was not accurate. Hence, we solved a problem that appears when using the Piso & Youdin (2014) method, which is one of the consequences of the inaccuracy of their method: the luminosity should decrease when the atmospheric mass decreases (given that the core luminosity is small, see Figure 3).

We also calculated a mass constant equivalent of the energy conservation for isolated systems to test our code further. We are currently adapting this code to the debris disk-specific constraints, and we expect to run many simulations with different parameters when it is ready.

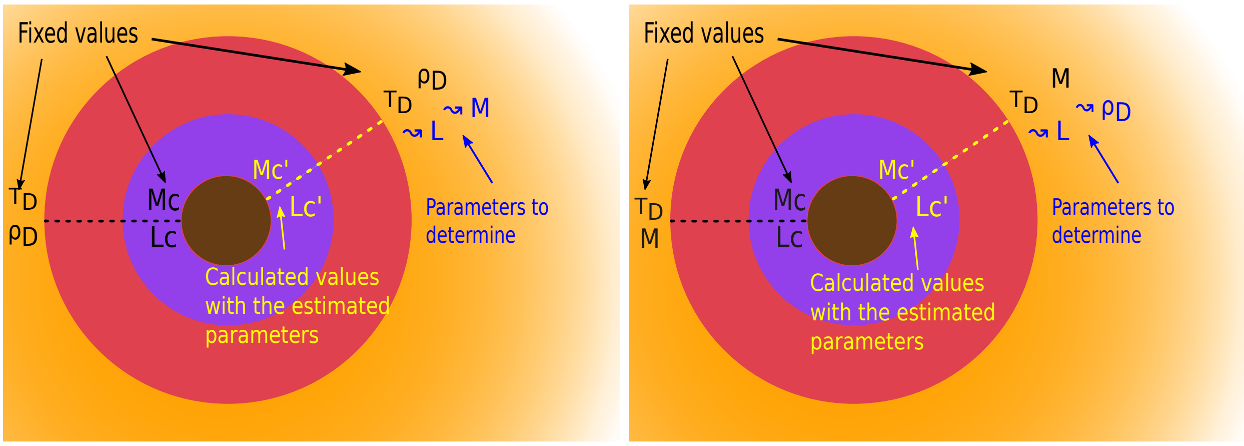

Fig. 2. Left: Boundary conditions for the case of protoplanetary disk conditions. **Right:** Boundary conditions for the case of debris disks with, e.g., lower disk density.

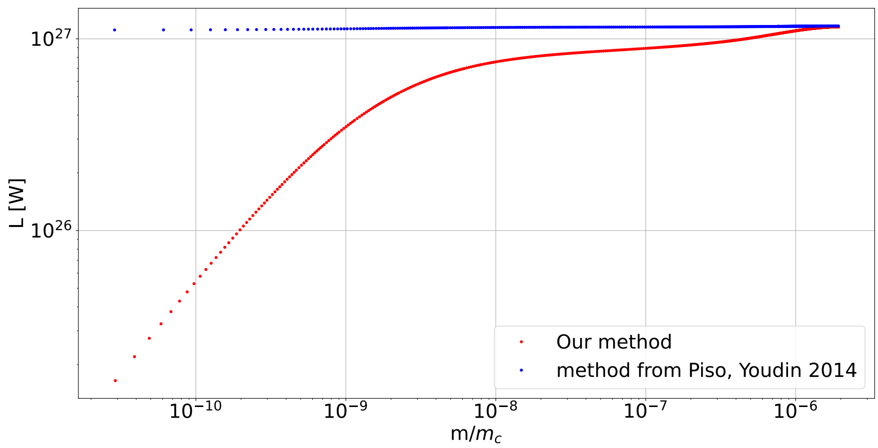

Fig. 3. Luminosity as a function of the mass ratio between the atmosphere and the core for a snapshot calculated by Piso & Youdin's method and by ours. With our method, the luminosity tends to 0 as the atmosphere's mass tends to 0. With the Piso & Youdin (2014)'s method, the luminosity tends to a constant of the order of the outer border luminosity, which is unphysical.

4 Conclusions

We are updating methods developed for protoplanetary disks to model planetary accretion of late gas in debris disks that can occur for hundreds of millions of years after the disappearance of the protoplanetary disk. We have validated the code against other published accretion models and are now in the process of including debris disk specificities including low gas density, lower accretion rates, and the effect of the core luminosity that may become important in this regime. The aim of this project is to gain a better understanding of the importance of late gas accretion in the final composition of the atmospheres of the planets affected. To do so, we will study the influence of the main parameters on the accretion rate: the temperature of the disk, both the compositions of the late gas and atmosphere, the gas production rate in the belt, and its density. Some other effects will be thoroughly investigated such as the effect of the core luminosity, and the influence of the initial conditions: mass of the solid core, and accretion onto an existing atmosphere...

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