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Dust filtration in revenant protoplanetary disks (Invited contribution)

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Abstract

Estrellas más masivas que el Sol, con masas entre 1.5 y $3M_\odot$, experimentan transformaciones notables en su estructura interna y temperatura efectiva durante los primeros millones de años de su existencia. Estos cambios afectan considerablemente a los discos protoplanetarios que se forman a su alrededor, impactando en los procesos de formación planetaria. Aquí investigamos los efectos de la evolución estelar en la evolución simulatánea de gas y sólidos en un disco renacido que orbita una estrella de $2.5M_\odot$. Este escenario ha sido descripto recientemente por Ronco et al. (2024), representando la reconexión de los discos interno y externo generada después de la apertura de una brecha debido a la fotoevaporación por la estrella central. Nuestras simulaciones muestran que, como era esperable, esta brecha también divide el disco sólido en dos, inhibiendo la migración radial de polvo/gravas desde las regiones externas, lo que podría limitar la formación de núcleos masivos cerca de la estrella. Sin embargo, una vez reconstruido el disco, el flujo de polvo/gravas se reactiva permitiendo que nuevo material alcance las regiones internas que podría contribuir a una formación tardía de Súper-Tierras.

Resumen

Stars more massive than the Sun, ranging between 1.5 and $3M_\odot$, undergo notable transformations in their internal structure and effective temperature within the first million years of their existence. These changes significantly affect the protoplanetary disks that form around them, impacting the processes of planetary formation. We here investigate the effects of stellar evolution on the simultaneous evolution of gas and solids in a revenant disk orbiting a $2.5M_\odot$ star. This scenario has been recently described by Ronco et al. (2024), portraying the reconnection of the inner and outer disks generated after a gap is opened by photoevaporation from the central star. Our simulations show that, as expected, this gap also divides the solid disk into two, inhibiting the radial drift of dust/pebbles from the outer regions, which may constrain the formation of massive cores near the star. However, once the disk is reconstructed, the dust/pebble flux is reactivated, enabling fresh material to reach the inner regions that could contribute to a late formation of Super-Earths.

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1. Introduction

Stellar evolution has been found to be a key ingredient in the evolution of protoplanetary disks around intermediate-mass stars. The dissipation timescales decrease as the mass of the central star increases, but the disk pathways show the typical inside-out disk evolution for all stellar masses Kunitomo et al. (2021). Ronco et al. (2024) expanded Kunitomo et al. (2021)'s work considering the effects of stellar evolution and adopting a finer grid of disk parameters, such as different disk masses and viscosities. These authors found that the evolutionary pathways of the gas disk in fact depend on the stellar mass, changing from the typical inside-out, to an homogeneous and to an outside-in evolution as the mass of the star increases. A particular pathway named "revenant disk evolution", has been found between the last two. In this scenario, and as a consequence of the changes of the X-ray and FUV photoevaporation rates

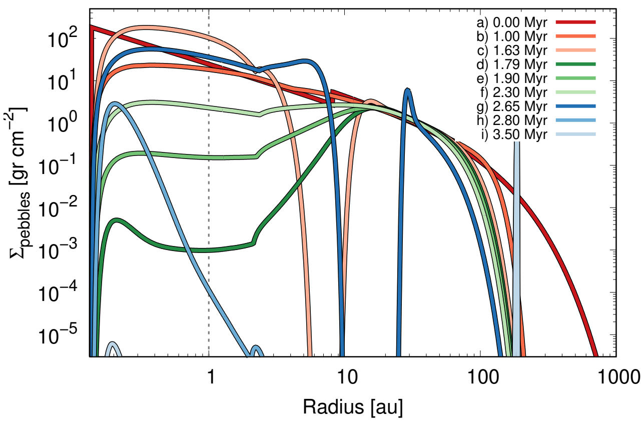

Figure 1. Time evolution of the solid surface density profiles for the disk case S33 (Ronco et al., 2024) for 1 mm pebbles. Each profile has a correspondence with the gas disk profiles of the revenant disk stages I, II and III, respectively, described in Sec. 3.4 of Ronco et al. (2024).

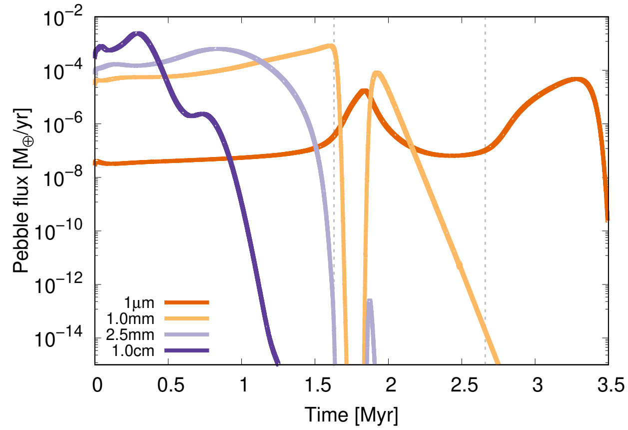

Figure 2. Time evolution of the dust/pebble flux of the revenant disk case S33 (sec. 3.4 in Ronco et al. (2024)) for different dust/pebble sizes, computed at 1 au. The gray dashed vertical lines represent the times at which the gap opens in the disk due to X-ray and FUV photoevaporation, respectively.

due to stellar evolution, the gas disk is reconstructed after the first gap opening by X-ray photoevaporation. We here explore how this particular case affect the evolution of the solid component of the disk and thus, on planet formation.

2. The model

The evolution of the gas component of the protoplanetary disk is computed as in Ronco et al. (2024). Because the dust/pebbles are strongly coupled to the dynamics of the gas, the time evolution of the dust/pebbles surface density is computed by solving a diffusion-advection equation,

$$\frac{\partial \Sigma_p}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\, v\, \Sigma_p\right) - \frac{1}{r}\frac{\partial}{\partial r}\left[r\, D^{*}\, \Sigma_g \frac{\partial}{\partial r}\left(\frac{\Sigma_p}{\Sigma_g}\right)\right] = \dot{\Sigma}_p, \quad (1)$$

where Σ_g and Σ_p are the gas and the dust/pebbles surface density, respectively, v the drift radial velocity, D^* the dust diffusivity and $\dot{\Sigma}_p$ the sink term due to dust/pebble sublimation (see details of the model in Venturini et al., 2020; Guilera et al., 2020). To keep this study as simple as possible, we do not compute the dust/pebble growth. Solids are always characterized by a single size along the disk and at every timestep. We run simulations only for the revenant disk case S33 (see sec. 3.4 in Ronco et al., 2024) and considering dust of 1 μm or pebbles of 1 mm, 2.5 mm and 1 cm. The initial dust/pebbles surface density takes into account the water-ice sublimation at the iceline, and the dust-to-gas ratio is taken as 1%.

3. Results

Figure 1 shows the time evolution of the solid surface density profiles for the disk case S33 formed by 1 mm pebbles. The first gap opened in the gas disk due to X-ray photoevaporation (see fig. 5 in Ronco et al., 2024) also opens a gap in the pebble surface density at 1.63 Myr (profile c). This gap limits the pebble flux from the outer region of the disk towards the inner ones as long as the gap exists. However, once the disk is reconstructed due to the combination of a strong decay in the X-ray photoevaporation rate and viscous evolution (profile d), pebbles drift inwards reaching the inner regions later on.

Figure 2 shows the time evolution of the pebble flux computed at 1 au for different solid particle sizes. For pebbles of 1 mm, the pebble flux abruptly decays just after the first gap opening (first dashed vertical gray line) but is reactivated once the disk is rebuilt, which may contribute to the late formation of Super-Earths at ∼1 au. However, the reactivation of the pebble flux depends on the particle sizes since this parameter is directly related to the radial drift velocity (see the recent review by Birnstiel, 2024). Particles smaller than 1 mm have drift velocities low enough not to empty the outer zones of the disk of solid material before the time of the first gap opening. For this reason, once the disk is reconstructed, there is still solid material that can flow towards the central star. On the other hand, particles with sizes greater than 1 mm have higher drift velocities. This causes the disks to lose most of its solid material rapidly before the time of gap opening. Subsequently, there is no longer material available in the outer regions to supply the inner ones after the disk reconstruction.

4. Conclusions

For particles with sizes lower than ∼1 mm we find pebble filtration in reventant disks. This pebble filtration towards the inner regions could promote the late formation of Super-Earths.

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