The Effects of Planet Formation in Dusty Disks on Stellar SEDs

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1 Introduction

The formation of planets is a complex and fascinating process that begins in the dusty disks surrounding protostars. Flattened, rotating gaseous protoplanetary disks around these young stars reprocess light from the central star, modifying the spectral energy distribution (SED) of the system, and revealing themselves in resolved images at various wavelengths Dong *et al.* (2015). As the protostar forms and evolves, the materials in the this disk interact in intricate ways, leading to the creation of planetesimals, the building blocks of planets.

Understanding the mechanisms that drive planet formation in these dusty environments is crucial for astronomers and astrophysicists. The study of protoplanetary disks offers insights into the initial conditions of planet formation, the migration and growth of planetesimals, and the eventual emergence of fully formed planets. These processes are influenced by various factors, including the composition of the dust and gas, the dynamics within the disk, and the influence of the emerging star's radiation and gravity. However, it is difficult to directly detect forming planets in disks, and only a few have been identified so far Dong *et al.* (2015), Observations using advanced telescopes, both ground-based and space-borne, have provided significant breakthroughs in our understanding of these early stages of planet formation. The Atacama Large Millimeter Array (ALMA), for instance, has allowed scientists to observe the intricate structures within protoplanetary disks, revealing gaps that indicate ongoing planet formation.

Theoretical models and simulations play a vital role in interpreting observational data and predicting the outcomes of different planetary formation scenarios. Due to their complexity, protoplanetary disk models have a large number of free parameters, which makes them both very flexible and computationally demanding (models frequently take several minutes or hours to run). For these reasons, disk modeling

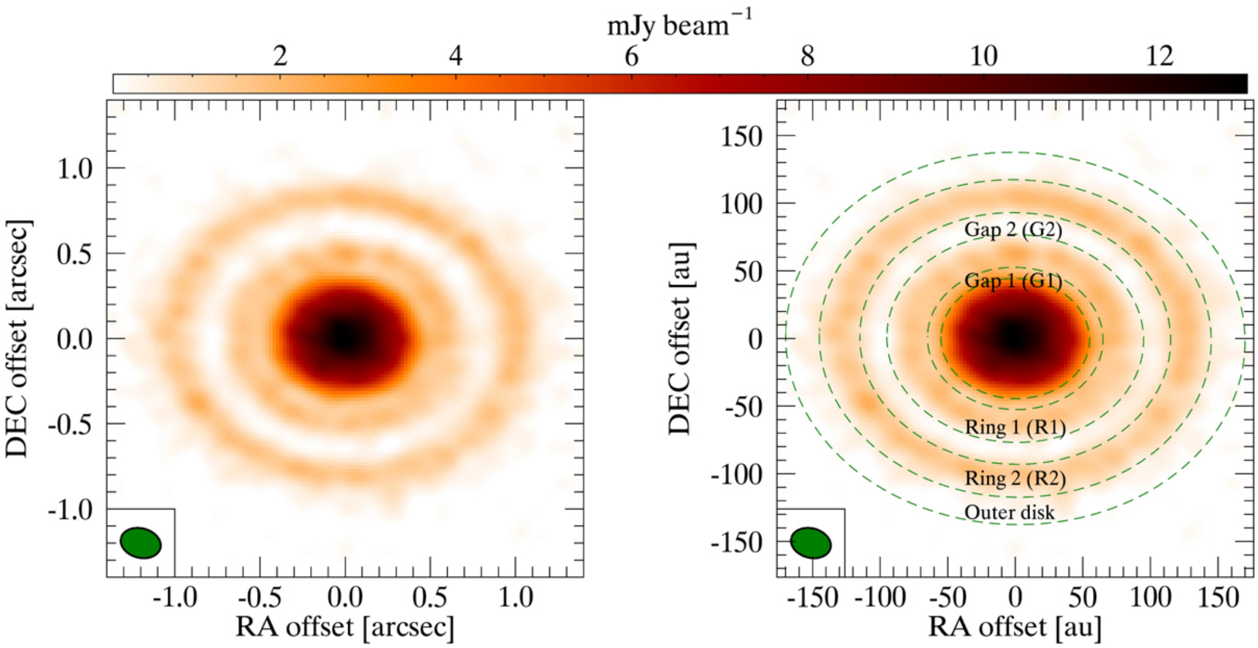

Figure 1: ALMA 1.3 mm dust continuum image (uniform weighting). The main substructures are highlighted in the right panel. From Fedele *et al.* (2018)

usually requires either fixing several parameters (some of which could be highly uncertain) or adopting more simplistic models, which limits the information that can be obtained from them. Ribas *et al.* (2020)

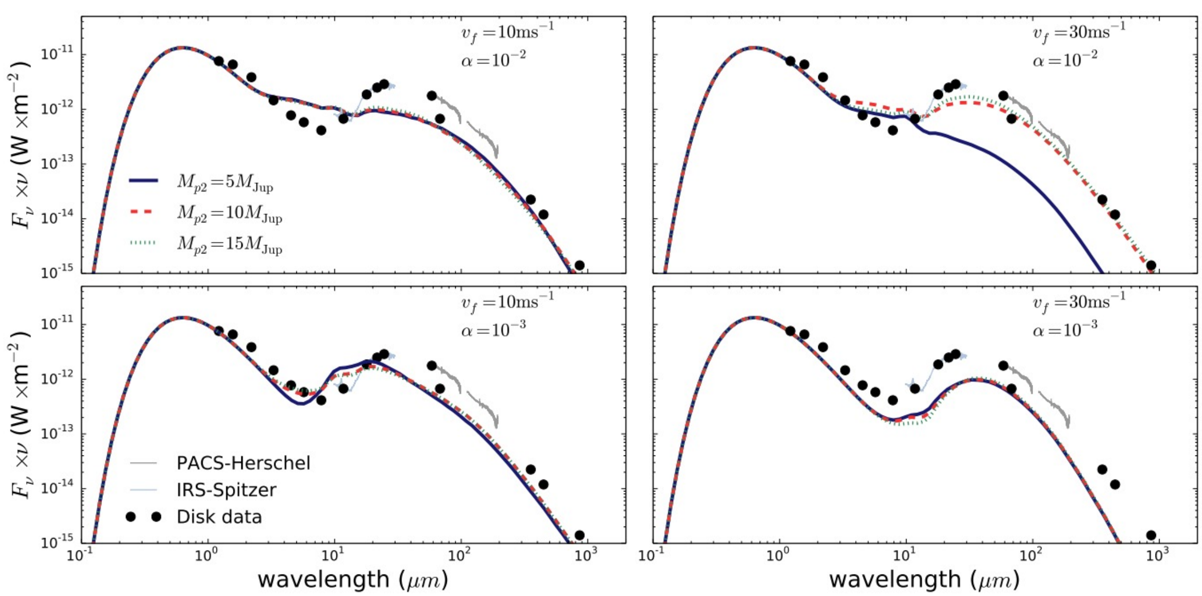

Figure 2: Spectral energy distribution (SED) resulting from the radiative transfer modelling, assuming grain size distribution after 1 Myr of evolution when two planets interact with the disk, and assuming different values for the disk viscosity α_{turb} and fragmentation velocity of particles v_f . From Pinilla *et al.* (2015)

The study of planets in the dusty disks of protostars not only enhances our understanding of the origins of planets but also provides a broader perspective on the diversity and complexity of planetary systems throughout the galaxy. As technology advances and our observational capabilities expand, the mysteries of planet formation continue to unravel, bringing us closer to answering fundamental questions about the universe.

2 Modeling Planets in Dusty Disks

2.1 Problem Setup

We assume a MMSN surface density profile ($\Sigma_{g,0} = 1700$ g cm^{-2}, $r_0 = 1$ au, p = 1) for the gas and an ISM gas to dust ratio $\epsilon = \Sigma_g/\Sigma_d = 100$. We assume a disk with an inner edge of $r_{min} = 0.1$au and $r_{max} = 100$au. Next, we will assume that the temperature profile is that of a passively irradiated disk in thermal equilibrium, $q = 1/2$, you with $T_0 = 273$ at $r_0 = 1$ au for a disk irradiated by a central protostar of $T_{star} = 4000K$ and $R_{star} = 2R_\odot$. We calculate the density of the dust using:

$$\Sigma_d = \Sigma_0 \epsilon (\frac{r}{r_0})^{-p} \tag{1}$$

We are going to plot the full SED for the disk and it's protostar as λF_λ where:

$$F_\lambda = \frac{dIdA}{d^2}, \tag{2}$$

where dI is the total intensity as a function of wavelength, dA is the area, and d is the distance in parsecs.

2.2 Tests

2.2.1 Gap Size

In order to simulate a planet that has consumed all the dust in their immediate area, we set the $\Sigma_d = 0$ throughout the entire area that would be the gap created by the planet. We test two different types of gaps created by the planet. The first gap size is determined by the Hill radius (Hill, 2022), r_h, which is defined as:

$$r_h = \frac{m_p}{3m_\star}^{1/2} r_p, \tag{3}$$

where m_p is the mass of the planet, $m_\star$ is the star mass, and r_p is the radius that the planet is orbiting at. The other method is using the values from Dong *et al.* (2015) of 10 Au.

2.2.2 Planet Distance

In order to determine of r_p affects the SED, we insert a planet at both 6 Au and 15 Au. We also set up a two planet system, where there is a planet at both of these locations and compare the resulting SED. The initial dust density, Σ_d, for the gap clearing is displayed in Figure 3.

3 Results

For the model using the Hill radius, there is no difference in the SEDs between the model without a planet and the one with planets. This is because the calculated gap is insignificant compared to the total radius of the disk. Using the model with values for gap size in Dong *et al.* (2015), a planet 6 Au shows a dip in the SED caused by the formation of a planet clearing out the dust. At 15 Au, the dip is significantly smaller than that caused by the planet closer to the star. These result are shown in Figure 4. These results show that a significant gap must be form in order to be detectable in the SED of a protoplanetary disk. Also, the closer to the star, the easier it is to detect the planet being formed.

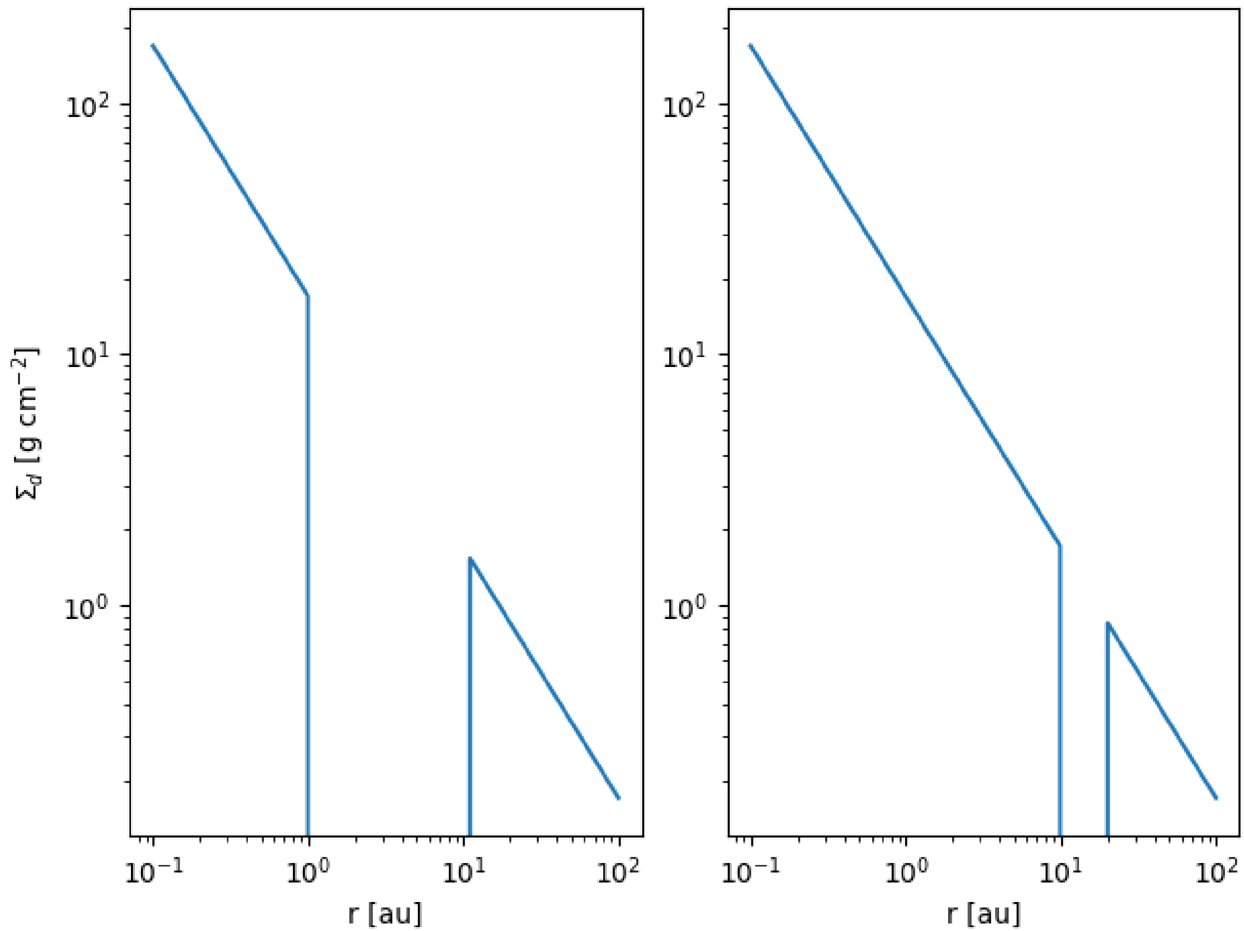

Figure 3: Σ_d as a function of radius for the model from Dong *et al.* (2015) for a star at 6 Au (right) and 15 Au (left)

4 Discussion and Summary

Overlll, we investigated the impact of planetary formation on the spectral energy distribution (SED) of a protoplanetary disk. Using a minimum mass solar nebula (MMSN) surface density profile and assuming an interstellar medium (ISM) gas-to-dust ratio, we examined how the formation of planets influences the SED by creating gaps in the disk. We adopted a temperature profile for a passively irradiated disk and calculated the dust density accordingly. Our primary focus was on simulating the effects of planets at different distances from the central star and comparing the resulting SEDs.

4.1 Gap Size and Its Impact on SED

The first part of our analysis tested gap sizes based on the Hill radius and a fixed gap size from Dong *et al.* (2015). Our findings indicated that gaps calculated using the Hill radius were too small to produce detectable changes in the SED. This suggests that the Hill radius may underestimate the extent of gap clearing by planets, making it challenging to identify planet formation through SED analysis alone.

Conversely, the fixed gap size of 10 AU provided by Dong *et al.* (2015) resulted in noticeable dips in the SED, particularly for a planet at 6 AU. This larger gap more effectively cleared dust, causing a detectable decrease in the SED. The results demonstrate that significant gaps are necessary to observe changes in the SED, highlighting the importance of considering larger gap sizes for detecting planetary formation.

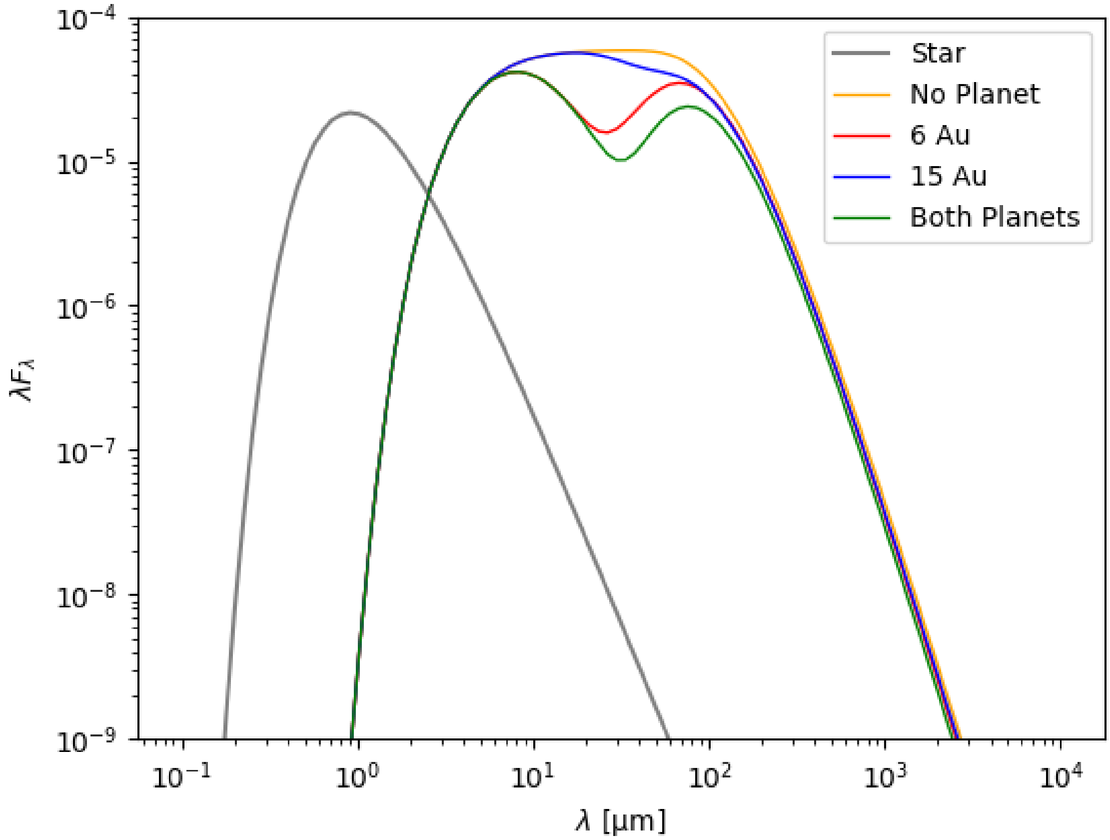

Figure 4: SED of the model with gap size of 10 Au. There is a significant dip in the λF_λ. For the planet at 15 Au, the drop is much smaller. For the combined SED of both planets, it matches up with the drop in λF_λ that each planet displays.

4.2 Planet Distance and SED Detection

The second part of our study examined the effects of planet distance on the SED. We placed planets at 6 AU and 15 AU and compared the resulting SEDs. A planet at 6 AU caused a more pronounced dip in the SED than a planet at 15 AU, indicating that closer planets have a greater impact on the dust distribution and are easier to detect. Additionally, in a two-planet system with planets at both 6 AU and 15 AU, the SED showed combined effects, further emphasizing that planets closer to the star create more noticeable features in the SED.

We highlight several key insights into the detection of planet formation through SED analysis of protoplanetary disks:

- **Gap Size Significance:** Only significant gaps, such as those based on the fixed size from Dong *et al.* (2015), produce detectable changes in the SED. Gaps calculated using the Hill radius are too small to be observed in the SED, suggesting the need for models that predict larger gap sizes.

- **Proximity to Star:** Planets closer to the star create more substantial dips in the SED compared to those farther out. This indicates that planetary formation closer to the star is easier to detect via SED analysis.

- **Combined Effects in Multi-Planet Systems:** In systems with multiple planets, the SED reflects the combined effects of all planets, which can complicate the interpretation but also provide richer data for analysis.

Overall, we underscore the importance of considering both the size of gaps created by planets and their distance from the star when analyzing the SED of protoplanetary disks. As observational techniques and technologies continue to improve, these insights will be crucial for identifying and understanding planetary formation processes in distant star systems.

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