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A NEW MECHANISM TO EXPLAIN THE NEAR-IR VARIABILITY OF THE TRANSITIONAL DISK OF GM AUR

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ABSTRACT

An ubiquitous feature of stellar systems, particularly of transitional disks, is their variability across the full range of the electromagnetic spectrum. The contribution to the near-infrared region of the spectrum comes mainly from the inner region of the disk, where gas and dust are heated to extremely high temperatures. We present a new physical mechanism that can explain the near-infrared variability of some transitional disks. The main process is the intermittent formation of a sublimation wall due to an instability between the magnetic field of the star and the innermost disk region. When the wall is present, it contributes to the spectrum but also shadows part of the material beyond its location. Using this mechanism, we present a model to explain the near-infrared variability of the transitional disk around GM Aur.

RESUMEN

Una característica común a los sistemas estelares, particularmente a los discos transicionales, es su variabilidad en el intervalo completo del espectro electromagnético. La contribución a la región del cercano infrarrojo del espectro proviene principalmente de la región interna del disco, donde el gas y el polvo se calientan hasta alcanzar temperaturas muy altas. Proponemos un nuevo mecanismo capaz de explicar la variabilidad en el cercano infrarrojo de algunos discos transicionales. El proceso principal es la formación intermitente de una pared de sublimación debida a una inestabilidad entre el campo magnético de la estrella y la región más interna del disco; cuando la pared está presente, contribuye al espectro pero también oculta parte del material más allá de este punto. Usando este mecanismo, presentamos un modelo para explicar la variabilidad en el cercano infrarrojo del disco transicional alrededor de GM Aur.

Key Words: instabilities — planets and satellites: formation — stars: pre-main-sequence

1. INTRODUCTION

In many surveys, young stellar objects (YSOs) show variability in the infrared region of the spectrum (Morales-Calderón et al., 2011; Kospal et al., 2012; Flaherty et al., 2013; Cody et al. 2014). In the optical band, the location and physical changes of the spots on the stellar surface (Lanza et al. 2006) produce optical variability (Herbst et al. 1994; Wood et al. 2000). The variability observed simultaneously in the optical and infrared spectral ranges (Eiroa et al. 2002; Stauffer et al. 2014) indicates a physical connection between the changes occurring in the star and the changes in the innermost dusty disk. Based on this connection, there are a couple of common explanations for the variability observed in the infrared: (1) obscuration of the star by dust structures such as clumps and disk warps (Flaherty & Muzerolle 2010; Morales-Calderón et al. 2011; Bouvier et al. 2013), (2) changes in the structure of the sublimation wall (Flaherty et al., 2013; Nagel et al. 2015). A detailed description of these physical mechanisms suggests that the observed optical variability should be interpreted based on the infrared variability (see Nagel et al. 2015 and references therein).

The stars with a transitional disk show persistent variability, and can show peculiar behavior in the near-infrared (NIR) and mid-infrared (MIR); for example, the variability observed in LRLL 31 changes at wavelengths smaller/larger than 8.5μm (Muzerolle et al. 2009; Flaherty et al. 2011). These authors argue that this can be explained by changes in the wall height. Some of the spectral variability of transitional disks can be ascribed to the presence of asymmetric structures that can be clearly seen at scales larger than a few AU (Casassus et al. 2013; Kraus et al. 2013; Boccaletti et al. 2013; Pérez et al. 2014; Benisty et al. 2015). A possible explanation of these structures is the presence of one or more planets embedded in the disk that alter the mass distribution (Masset et al. 2001; Dodson-Robinson & Salyk 2011; Casassus et al. 2013; Sallum et al. 2015; Alvarez-Meraz et al. 2017). Planetary influence is evident in LkCa 15 because there is evidence of material falling towards the innermost planet (Sallum et al. 2015). These structures can also be seen inside the hole, as in the case of a transitional disk in Upper Scorpius (Mayama et al. 2012) ; they can also be inferred in the transition disk J160421.7-213028 from a warp in the inner disk or circumplanetary material that creates a shadow that can be detected as a flux dip (Pinilla et al. 2015). These asymmetries can naturally extend towards the innermost regions, becoming an important element to take into account when interpreting the variability.

Ingleby et al. (2015) reported variations in the ultraviolet (UV), optical and NIR regions of the spectrum of the transitional disk of GM Aur in Taurus, from observations separated by one week and 3 months. In the same work, the authors presented a model for explaining the variability in the UV and NIR regions of the spectrum for two epochs separated by 3 months. Their model takes into account how the characteristics of the hot accretion spot change with changes in the stellar mass accretion rate ($\dot{M}$). Regarding the variability in the NIR region, the model implies changes in the amount of optically thin material present in a small inner disk. The presence of this disk was part of the model developed by Calvet et al. (2005) and, afterwards, by Espaillat et al. (2010).

Ingleby et al. (2015) said that a weakness of their model is that the variations in the amount of material in the inner disk that occurred during the time span of the observations, and which are used to explain the amplitude changes in the NIR, are not consistent with the viscosity timescale. Another problematic issue is that $\dot{M}$ varies between the two epochs, implying the occurrence of structural changes in the innermost disk region.The explanation proposed by Ingleby et al. (2015) is that a magnetic instability can modify the structure of the disk by interaction with the stellar magnetic field (D'Angelo et al. 2012). This kind of mechanism is also invoked by Flaherty et al. (2011); in this case, the idea is that this interaction leads to a variable scale height of the sublimation wall and/or to warping of the inner disk. From the physical point of view, the magnetic instability produces an overdensity around the corotation radius (R_{cor}: the location where the angular velocity of the disk, Ω_d, matches the rotational angular velocity of the star $\Omega_\star$). The material is retained at this place until it eventually falls into the star, resulting in high and low $\dot{M}$ states: $\dot{M}_{high}$ and $\dot{M}_{low}$. This mechanism requires the existence of a disk in the inner hole, as in the case of PDS 70 (Dong et al. 2012) and Sz 91 (Tsukagoshi, T. et al. 2014). The presence of material in the innermost regions is physically expected because matter accretion towards the star has been detected in many of these systems (Rosenfeld et al. 2014; Mendigutía et al. 2015).

In this work, we propose a new mechanism that could explain the variability observed in the NIR of some systems. The model is based on the following assumptions: (1) the accumulation of matter caused by the magnetic instability is enough to produce an optically thick region; (2) since this region is located around the sublimation radius, a sublimation wall is formed; (3) the components that explain the NIR variability are the sublimation wall and the optically thin material in the gap. The sublimation wall hides some of the optically thin material that contributes to the stellar radiation, and so the presence of the wall reduces the emission from this material without the need of decreasing the amount of material inside the gap. This means that the model is consistent with the viscosity timescale of the inner disk, while also reducing the emitting contribution of the thin material. The model is described in § 2. § 3 shows the results and includes a discussion of it. § 4 presents the conclusions.

2. MODEL

2.1. *Motivation*

The aim of this work is to propose a new explanation of the variability in the NIR region of the spectrum of GM Aur observed in 2 epochs. The object is located in the Taurus molecular cloud at a distance of 140 AU; the system inclination ($\approx 57°$) is taken from Dutrey et al. (1998). The spectra spanning the range $0.8 - 5.4\,\mu$m were obtained with the SpeX spectrograph on board of NASA's Infrared Telescope Facility. These spectra were first reported by Ingleby et al. (2015): the observation made during September 11th 2011 is named GM-1 and the one made during January 6th 2012, is named GM-3. We use these names throughout this paper. Ingleby et al. (2015) attributed the NIR variability to changes in the emission from the hot accretion spot due to variations in $\dot{M}$, and to differences in the amount of the optically thin material located in the hole in both epochs. Note that systems cataloged as having a transitional disk are still able to sustain small inner disks (Avenhaus et al. 2014). Previously, Espaillat et al. (2011) required the presence of a small optically thin inner disk to model the Spitzer spectrum of GM Aur.

The model presented by Ingleby et al. (2015) requires changes in the global structure of the inner disk to explain the observations. These changes occur over the viscous timescale ($\approx$ several years) but the time span between observations is 3 months. Thus, the model cannot be valid given the disparity between both time scales. The mechanism presented in § 2.2 is consistent with the viscous timescale and also requires the presence of an optically thin inner disk.

2.2. *New Variability Mechanism for the Disk Spectrum*

Ingleby et al. (2015) state that the structural changes in the system should occur in the innermost region of the disk in order to explain the timescale of the observed variability. The relevant timescale is the free-fall time of the gas flowing along the magnetic field lines towards the star, where the hot accretion spot is formed. A mechanism that explains the locally concentration of material accreting at the disk is also required to explain the variable $\dot{M}$. Ingleby et al. (2015) refer to a magnetic instability described in D'Angelo et al. (2012) to satisfy the requirements: a concentration of material in the vicinity of the magnetosphere. This instability is activated in T Tauri stars with magnetic fields $B \sim 1$kG, which are typical for this type of stars (Yang, H. & Johns-Krull 2011; Johnstone et al. 2014). This is a local effect that can produce the concentration of matter. However, it is important to note that there are physical mechanisms inside the disk that are responsible for creating asymmetrical structures, such as the spiral arms observed at a few tens of AU (Benisty et al. 2015; Avenhaus et al. 2014). These structures become a boundary condition for the innermost region of the disk, leading to an asymmetrical stellar accretion. The presence of this kind of structures is a natural way to explain some of the observed variability in $\dot{M}$, as is the magnetic mechanism described above (D'Angelo et al. 2012).

The new element introduced in the model presented here is that a concentration of material in an optically thin disk can locally turn into an optically thick structure, like a wall. Note that the disk can be optically thin in the line of sight and optically thick with respect to the stellar radiation, which is approximately parallel to the disk midplane. Also note that the radiation crosses a larger amount of material moving along the midplane than in the vertical direction. In sum, in this model, the formation of a wall requires an optically thick region obscuring some of the stellar radiation; this region can exist even though the disk is optically thin in the vertical direction (Mulders et al. 2010).

We do not know the precise hydrodynamical behavior of the magnetic instability in the disk, only that it acts in a small radial region. The accumulated dust can come from the inner, outer and/or upper adjacent zones. Given these unknown factors, it is not possible to estimate the changes in the gas density that are required to create an optically thick region. Another physical aspect worth noting is that the evaporation and condensation of dust can change the amount of dust in a region where the sublimation front is located. The location of the front must vary in time because the luminosity of the star (including the accretion luminosity) changes between both epochs. The dust evaporates in a few hours (Shu et al. 1996) and condenses in a time-scale of weeks (see a discussion of this in Nagel et al. 2015). These timescales are well within the 3 months span between the modeled observations. Besides, 3 months is a lower limit for this process because the observations do not cover a full cycle (high-low-high states). It is worth noting that during the stage of accumulation of matter, the accretion luminosity decreases and the sublimation front recedes to a location closer to the star, causing the appearance of "new" dust in the region. These dust grains increase the optical depth of the layer where the wall will be formed. This process is not directly related to the magnetic instability because it does not require density changes. Our model allows us to estimate how much the dust density changes in response to the magnetic instability that explains the spectral variability. The mass hidden by the wall is $1 \times 10^{-12} M_{\odot}$, the minimum location of the wall is $R_{min} = 0.0452\,\mathrm{AU}$, and the wall height is $z_{wall} = 6 \times 10^{-4}\,\mathrm{AU}$ (Table 2). According to these values, the mean dust surface density paralell

TABLE 1

STELLAR PARAMETERS

Parameter	Epoch GM-1	Epoch GM-3
$T_{\rm spot}$(K)	6194	5241
f	0.031	0.041
$M_\star(M_\odot)$	1.1	1.1
$R_\star(R_\odot)$	1.7	1.7
$T_\star$(K)	4350	4350

TABLE 2

PARAMETERS OF THE MODEL

Optically thin inner disk		
Parameter	Epoch GM-1	Epoch GM-3
$R_{\rm min}$(AU)[a]	0.008	0.008(0.0499)
$R_{\rm max}$(AU)[a]	1.0	0.0452(1.0)
$M_{\rm d}(M_\odot)$	1.9×10^{-12}	0.9×10^{-12}
Sublimation wall		
$R_{\rm in}$(AU)	···	0.0452
$R_{\rm out}$(AU)	···	0.0499
$z_{\rm max}$(AU)	···	0.0006

[a]In parentheses are the values for the region radially outwards from the wall.

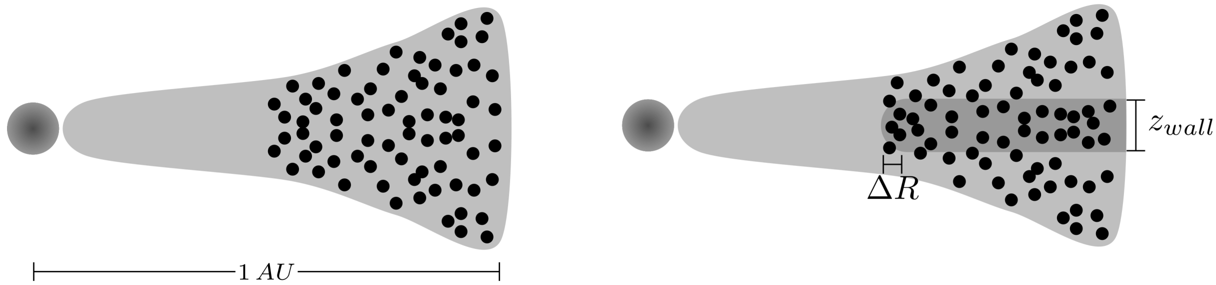
to the disk is $5.27 \times 10^{-2}\,{\rm g\,cm^{-2}}$, and based on the increased abundance of large grains in the midplane layer (a factor of 12.4 times the standard value 0.01, see § 3) the gas density is $0.425\,{\rm g\,cm^{-2}}$. Considering $\kappa = 1.77\,{\rm cm^2\,g^{-1}}$ as a typical opacity in the stellar wavelength range (D'Alessio et al. 2001), the optical depth is 0.75. From this value, we can argue that a change by a factor of 1.4 in dust density is enough to increase the optical depth to 1, making this region optically thick, as required.

We propose two states that intermittently change from one to the other. These states are: presence or absence of a wall. This scenario requires changes in dust density, which in turn requires a concentration mechanism. The general idea is that a sublimation wall intermittently appears (GM-3) and disappears (GM-1) due to a magnetic instability acting in the boundary between the magnetosphere and the disk. This structure must be close to the magnetospheric radius to activate the magnetic instability (D'Angelo et al. 2012). Ingleby et al. (2015) also propose a connection between the variability in the far UV and the NIR for GM Aur, establishing a close association between gas and dust emission. The changes in the sublimation wall affect dust (variations in its emission) and gas (variability in $\dot{M}$) equally. This wall contributes to the spectrum in two ways: it is a new emission component but also acts as a shield against stellar radiation for some of the material in the optically thin inner disk. Note that this dense structure is not long-lived because the material inside it should eventually fall towards the star along the stellar magnetic field lines. In sum, the system transitions between a high accretion state (without a wall) and a low accretion state (with a wall, see Figure 1). In this work, we suggest that: (1) in the former state, the optically thin dust emission from the inner disk completely explains the excess emission above the predicted stellar spectrum (which includes the emission from the accretion spot); (2) in the latter state, the excess emission is explained by both the optically thin dust and the sublimation wall.

2.3. *Description of the Model*

This model considers three contributors to the spectrum of GM Aur: the spotted star, the optically thin inner disk and the sublimation wall. The difference in stellar emission between both epochs (GM-1 and GM-3) was modeled using blackbodies to represent the star and the hot accretion spot. The temperature of the spot was estimated using the fit of the UV and the optical spectra of the epochs GM-1 and GM-3, which are reported in Ingleby et al. (2015). We took the energy flux of the magnetospheric flow F and the stellar surface coverage f from Table 2 in Ingleby et al. (2015) and associated the former with a spot temperature (T_{spot}) as described in Ingleby et al. (2013). The parameters T_{spot} and f allowed us to find a blackbody model for the accretion spot and to correct the stellar contribution accordingly. The stellar parameters were taken from Ingleby et al. (2015) ; we assumed that they remained constant between epochs GM-1 and GM-3. Table 1 shows the values associated to these parameters.

The emission of the optically thin inner disk was taken from Figure 4 in Ingleby et al. (2015). Note that because we assumed that the spatial distribution of the dust remained the same between epochs GM-1 and GM-3, and the material was optically thin, the shape of the spectrum did not change. The sublimation wall emission was modeled as in Nagel et al. (2013), taking into account the vertical density profile of the disk and the settling of dust in



(a) High state (b) Low state

Fig. 1. Diagram of the high and low accretion states of the disk. The points represent dust particles. In the low accretion state there is a sublimation wall with thickness ΔR and height $z_{\rm wall}$: note that at radii smaller than that of the wall there are no dust grains.

the midplane (Isella & Natta 2005; Tannirkulam, A. et al. 2008). We assumed that the outer radial boundary of the wall ($R_{\rm out}$) is such that the radial zone spanning the wall must be inside the optically thick region. As mentioned in § 1, this region is associated with the magnetically unstable region described in D'Angelo et al. (2012). From Figure 3 in D'Angelo et al. (2012), we used $\Delta R = 0.15 R_{\rm in}$ as a typical value for the unstable zone size, where $R_{\rm in}$ is the inner radial location of the disk. We assumed that $R_{\rm in}$ is equal to the magnetospheric truncation radius $R_{\rm mag}$ which is equal to $5R_\star$ (Calvet & Gullbring 1998). To explain the formation of the sublimation wall, we assumed that the density of the dust in the unstable region becomes large enough to be optically thick to the stellar radiation. In § 2.2 we mention that the observed timescales for the variability in the NIR and UV regions are equal, which indicates that the dust and gas in the inner regions of the disk are closely related to each other. This requires that the sublimation radius ($R_{\rm sub}$) is close to $R_{\rm in}$, which is possible if one assumes a settled layer of large dust grains around the midplane.

If one assumes the presence of a sublimation wall in the disk, it is necessary to characterize the dust that forms it. Dust abundances are assumed to be the same as in Nagel et al. (2015). The maximum radius of the dust grains is $a_{\rm max} = 1$mm and the settling of the dust is parameterized as in D'Alessio et al. (2006) using $k = 20$ (which characterizes the vertical transition between small and large grains), and $\delta = 1$ (which gives the height of the midplane layer of large grains in units of the pressure scale height). The last value is consistent with estimates of the height of the settled dust such as those made by Takeuchi & Lin (2002). By making a detailed analysis of the motion of particles with different sizes, they found that the particles should settle towards the midplane. In the models of Takeuchi & Lin (2002), a layer defined by $\delta = 1$ is completely settled when it has the same parameters used here. Dullemond & Dominik (2004) estimated a dust depletion height, the height above which all the grains of a certain size are removed by settling. The value they estimated is a few times the pressure scale height, which means that a layer defined by $\delta = 1$ settles in the way assumed by our model. A reasonable model of dust settling should include physical effects such as turbulence and account for how the gas affects the motion of the particles. For instance, an increase in the turbulence parameter α should cause an increase in viscosity and reduce the effectiveness of the settling process to maintain a settled layer of large grains. An increase in gas density has the same effect because the stopping time decreases and the particles stay longer at high latitudes. These effects are taken into account in the model of Takeuchi & Lin (2002). A value of $\epsilon = 0.01$ characterizes the depletion of the small grains with respect to the standard dust-to-gas mass ratio. In our model, the settling process described by these parameters occurs throughout the inner disk; its radial range is shown in Table 2. We choose a small value of ϵ to characterize a large depletion of small grains, due to the large amount of big grains that are involved in the settling process. This is required to explain the difference in the amount of optically thin material that contributes to the emission between epochs GM-1 and GM-3 (see § 3 for a full explanation).

The radial location of the wall along the vertical direction is estimated by taking into account that the sublimation temperature $T_{\rm sub}$ depends on the dust density (Isella & Natta 2005; Tannirkulam, A. et al. 2008). The values that describe the association of $T_{\rm sub}$ with density were taken from Table 3 in Pollack et al. (1994).

3. RESULTS AND DISCUSSION

In § 2 we described a new mechanism for the interpretation of the NIR variability observed in the stellar system GM Aur. In this section, we will prove that the hypothesis presented in § 2.2 is reasonable. The hypothesis is that the observations of GM Aur can be explained by a sublimation wall that intermittently appears and disappears, due to a magnetic instability acting in the boundary between the magnetosphere and the disk. Figure 2 shows the modeled spectra for the star, the accretion shock, the optically thin gap material and the wall at the epochs GM-1 and GM-3. It can be clearly seen that the region of the sublimation wall is a strong contributor to the NIR spectrum. The presence of dust consisting of silicates is indicated by the peak at 10μm. When the wall is present (in epoch GM-3), it hides part of the optically thin disk from the stellar radiation, decreasing its contribution to the spectrum. The minimum and maximum radii of the wall are $R_{\rm in} = 0.0452$ and $R_{\rm out} = 0.0499$ AU, respectively. The height of the wall in $R_{\rm out}$ is $z_{\rm max} = 6 \times 10^{-4}$ AU. During the epoch with no wall, the whole SED (spectral energy distribution) is interpreted as emission from the optically thin dust. During epochs GM-1 and GM-3, the dust mass emitting in the inner disk is $M_{\rm d} = 1.9 \times 10^{-12}\, M_{\odot}$ and $M_{\rm d} = 0.9 \times 10^{-12}\, M_{\odot}$, respectively. The physical values associated to the components of the system are summarized in Table 2.

Note that the epoch GM-1 is modeled just as in Ingleby et al. (2015), and thus the optically thin mass is the same in both works. For the epoch GM-3, the modeled spectra of the existing components were obtained as described in § 2.3.

The difference in the amount of material in the optically thin disk between both epochs is not due to changes in the overall structure of the inner disk in the time span between both observations, since this timespan is not consistent with the viscous timescale of the disk; it is rather due to changes in the amount of material hidden by the sublimation wall. The difference in the emitting material can be explained by assuming that the material in the disk settles towards the midplane. A first estimation of the amount of hidden material can be done using the expressions found in the Appendix of Espaillat et al. (2010), which described the geometrical occultation of each ray coming from the star by an optically thick wall. In our model, the wall is vertically small and its size z_{wall} is similar to $R_{\star}$, which results in an hidden region that can be represented by a vertical layer of size z_{wall}; since the rays coming from the edges of the star, which intersects the upper part of the wall, are almost parallel to the disk plane (see Figure 1). If we assume a density profile defined by $\rho \propto \exp(-\frac{z^2}{2H_p^2})$, where $H_p = c_s/\Omega_K$ is the pressure scale height and c_s and Ω_K are the sound speed and keplerian angular velocity, respectively, and assume a typical surface density defined by $\Sigma \propto R^{-3/2}$, then the fraction of mass hidden by the wall is 0.116. If the dust is well-mixed with the gas, then this fraction should be equal to the optically thin mass in the GM-1 epoch minus the mass in the GM-3 epoch, in units of the mass in the GM-1 epoch, which is 0.53.

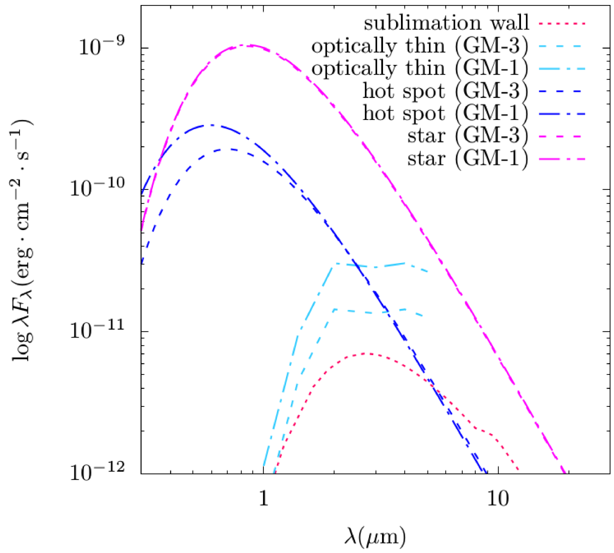


Fig. 2. The modeled stellar spectrum, the accretion shock, the optically thin gap material and the wall at epochs GM-1 and GM-3. For epoch GM-1 (dot-dashed lines), the emission from the star (magenta), the accretion shock (blue) and the optically thin material (cyan) are shown. The same for epoch GM-3, represented with dashed lines. In the latter case, we include the sublimation wall spectrum as a red dotted line. The color figure can be viewed online.

The difference between these values means that the inner disk should be settled. We take this into account in the model because the settling of material in the wall is parameterized as in D'Alessio et al. (2006) with a decrease in the abundance of small grains from $\epsilon = 1$ to $\epsilon = 0.01$. Table 2 shows the

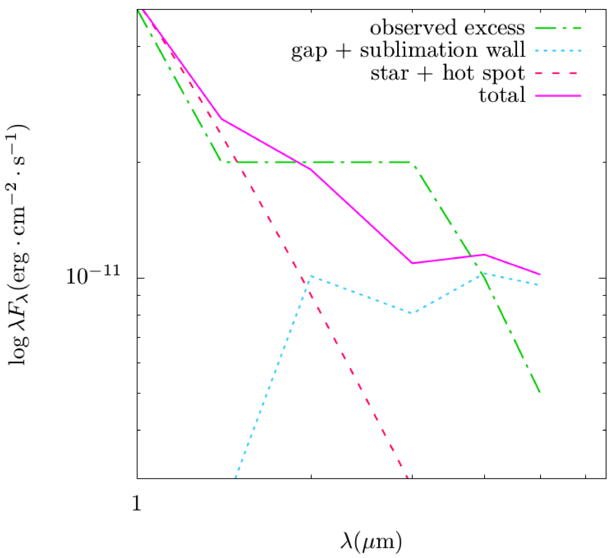


Fig. 3. The observed and modeled emission excess at epoch GM-1 compared to epoch GM-3. The observed excess is plotted as a dot-dashed green line. The modeled excess corresponds to: the star with a hot accretion spot (dashed red line), and the material in the gap created by the sublimation wall (dotted cyan line). The model with all the contributions is shown as a solid magenta line. The color figure can be viewed online.

radial range of the inner disk. The missing mass corresponding to small grains is now located in the midplane layer of large dust grains, the abundance of which is increased from 1 to 12.4. The order of magnitude increase in the mass of large grains fully accounts for the increase in the required mass fraction hidden by the wall (for dust well-mixed with gas in the disk) from 0.116 to 0.53. Note that the transition between small and large grains means that the abundance of the latter is not uniform in the layer hidden by the wall; however, the increase in abundance is large enough to ensure that the required amount of material is hidden in this scenario.

Figure 3 shows the details of the spectral differences between epochs GM-1 and GM-3. The observed spectrum was taken from Figure 4 in Ingleby et al. (2015). For the purposes of this work, we only used some reference values without considering the high dispersion of the data. Considering the uncertainty of the data, our model is able to explain the observations. The important result is that the physical mechanism proposed here is consistent with the observed NIR variability.

For the same purpose, Espaillat et al. (2011) analyzed an observed variability in the MIR range of GM Aur. They argued that an increase in the height of the wall located at the inner edge of the outer optically thick disk was responsible for the variations in the spectrum between two observations. Physically, when the wall grows, the emission at lower wavelengths increases but the emission at larger wavelengths decreases; this is because a larger region of the outer disk is shadowed by the wall. The presence of a small sublimation wall cannot explain the observed changes in the MIR flux. It could only explain it if the sublimation wall were able to shadow a part of the outer wall, causing variations in its flux with no need for changes in the wall height, as the model of Espaillat et al. (2011) suggests. However, the fraction of the outer wall obscured by the inner wall is just 1.87×10^{-4}, much less than the fraction required by the model of Espaillat et al. (2011), which is $0.3/3.2 = 0.0937$. The large difference between these values means that the changes observed in the MIR region cannot be explained by a shadowing effect of the sublimation wall. The second possibility to explain the variability assuming a small sublimation wall would be that the emission of the inner wall changed from one epoch to another. What actually happens is that , in this wavelenght range, the emission decreases notoriously compared with the NIR, as can be seen in Figure 3. The amount of variability observed in the MIR region ($\approx 10^{-11}$) is larger than the flux coming from the sublimation wall ($\approx 10^{-12}$); thus, even the intermittent appearance and disappearance of the wall is not enough to explain the variability observed by Espaillat et al. (2011). The remaining physical mechanisms that could be able to explain the MIR variability are related to the outer disk, which is far away from the region affected by the magnetic instability assumed in our work; therefore, their study is beyond the scope of this work.

4. CONCLUSIONS

1. The variability observed in the NIR spectrum of GM Aur can be explained by the intermittent formation of a sublimation wall inside an optically thin inner disk. In this scheme, the mass is divided into the fraction hidden by the wall (when it is present) and the fraction that forms part of the inner disk.

2. The inner dusty regions of the disk must be highly dynamic, since the intermittent formation of a sublimation wall formation is expected to occur in them. In a transitional disk, this defines two stages of the contribution of the dust

to the spectrum: in the first stage only the optically thin material contributes, while in the second stage there is also the contribution of the sublimation wall.

3. The variability mechanism proposed here works for disks with a large enough amount of dust in the hole, such that, when it accumulates, it turns an optically thick region into an optically thick region, which then becomes a new contributor to the spectrum.

4. In the case of GM Aur, the dust settles towards the midplane. This is a requirement of the model because the sublimation wall should hide a considerable amount of dust of the inner disk. Note that an unsettled disk explains much less variability than a settled one.

5. This mechanism reconciles the spectrum variability observed in a time span shorter than the viscosity timescale. Invoking a shadowing effect suggests a connection between a highly dynamic process (disk-magnetic instability) and variations in the contribution of the slowly evolving outer section of the disk.

The interaction between the stellar magnetosphere and the innermost regions of the disk was not studied here in depth due to its inherent complexity. A complete analysis of the physics acting in this region should consider other sources of spectral variability when modeling specific objects. This work focused on only one possible mechanism to explain the variability observed in the near-IR region of the spectrum of GM Aur.

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