MID-INFRARED VARIABILITY OF THE BINARY SYSTEM CS Cha

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ABSTRACT

CS Cha is a binary system surrounded by a circumbinary disk. We construct a model for the inner disk regions and compare the resulting synthetic spectral energy distribution (SED) with Infrared Spectrograph spectra of CS Cha taken at two different epochs. For our model, we adopt a non-axisymmetric mass distribution from results of published numerical simulations of the interaction between a circumbinary disk and a binary system, where each star is surrounded by a disk. In particular, we approximate the streams of mass from which the inner circumstellar disks accrete from the circumbinary disk. This structure is due to the gravitational interaction of the stars with the disk, in which an array of disks and streams is formed in an inner hole. We calculate the temperature distribution of the optically thin dust in these inner regions considering the variable impinging radiation from both stars and use the observations to estimate the mass variations in the streams. We find that the SEDs for both epochs can be explained with emission from an optically thick inner edge of the circumbinary disk and from the optically thin streams that connect the circumbinary disk with the two smaller circumstellar disks. To the best of our knowledge, this is the first time that the emission from the optically thin material in the hole, suggested by the theory, is tested against observations of a binary system.

Key words: circumstellar matter – infrared: stars – stars: pre-main sequence

1. INTRODUCTION

Studying the behavior of variability in T Tauri stars surrounded by disks can lead to a better understanding of their host stars as well as their disk structure and evolution. With observations obtained by the Spitzer Space Telescope (Werner et al. 2004) new detailed studies of mid-IR variability have become possible. Several mechanisms have been proposed to explain the different behavior observed in several young circumstellar disks. For instance, Muzerolle et al. (2009) found that the mid-IR spectral energy distribution (SED) of LRLL 31 in IC 348 varied on the scale of days, with a characteristic “seesaw” shape, i.e., as the emission decreased at wavelengths shortward of ~8.5 μm, it increased at longer wavelengths. Muzerolle et al. (2009) proposed that this type of variability reflected changes in the height of the inner disk edge.

Some infrared variability has been explained by changing the location of the inner disk edge. IR variability was found by Sitko et al. (2008) in HD 31648 and HD 163296 in the near-infrared (NIR) range (specifically between 1 and 5 μm), where the changes could be attributed to variations in the location of the dust sublimation zone. Modeling under this assumption shows that the sublimation wall (boundary between the dusty and the dust-free regions of the disk) varies between 0.29 AU and 0.35 AU for HD 163296. However, any variation of the material in the inner region, not limited to changing the location of the inner disk edge, could be responsible for the observed NIR variability.

Some of the intrinsic variability in circumbinary disks comes from the fact that the position of the stars is constantly changing along their orbits. Thus, the stars’ irradiation of the disk also changes, resulting in variation in the observed disk emission. This behavior can be seen in Nagel et al. (2010), where the predicted variation of the dust emission is presented for the binary system CoKu Tau/4. Jensen et al. (2007) also show that the emission of the binary UZ Tau E is clearly periodical. They explain this behavior with emission from material that flows from the circumbinary disk toward the stars. The orbital motion of a binary system and its interaction with the circumbinary disk has been proposed to be responsible for variability on the scale of years for UY Aur (Berdnikov et al. 2010).

Espaillat et al. (2011) have presented the largest modeling study of mid-IR variability in disks around T Tauri stars. Most of their sample, composed of transitional and pre-transitional disks, show seesaw variability, that was explained as a result of variations in the height of the inner disk edge. However, CS Cha, the only known circumbinary disk in their sample, shows variations only in the 10 μm silicate emission band. Based on SED modeling, Espaillat et al. (2011) inferred a hole size in the disk of about ~38 AU, and this large size implies that the inner disk edge is too far from the stars to have a temperature high enough to contribute at the ~10 μm emission. In their model, this 10 μm emission was produced by uniformly distributed optically thin dust inside a radius of ~1 AU, centered around a single star, and the observed variability was interpreted as due to variations in the mass of this optically thin dust.

CS Cha is an interesting laboratory to compare the observations to simulations of the interaction between the circumbinary disk and the binary system. In this paper, we construct a model that takes into account results from published numerical simulations of the circumbinary disk dynamics (Günther & Kley 2002; Günther et al. 2004; Artymowicz & Lubow 1994, 1996), and aim to constrain these simulations by comparing with the variability observed in the Infrared Spectrograph (IRS) spectra presented by Espaillat et al. (2011). In particular, we take into account that the predicted mass distribution within the inner hole is non-axisymmetric; it is characterized by streams connecting the edge of the circumbinary disk with the smaller circumstellar disks that surround each star. We find that these streams and the circumstellar disks are the main contributors to the emission at
10 μm. Since this material has a very low density, we calculate the temperature as a function of grain size assuming each grain is in radiative equilibrium with the radiation fields of both stars.

The paper is organized as follows. Section 2 summarizes the observations, already described in Espaillat et al. (2011). The model is described in Section 3, with particular detail given to how we estimate the spatial distribution of dust and calculate its temperature. The model input parameters, both those taken to be fixed and those adopted as free parameters, are described in Section 4. Section 5 describes the results and, finally, Section 6 presents the summary and conclusions of the paper.

## 2. OBSERVATIONS

CS Cha was observed at three different times. The first spectrum was obtained through the IRS Guaranteed-Time Observations (GTO), on 2005 July 11, and was previously presented in Espaillat et al. (2007a), Kim et al. (2009), Furlan et al. (2009), and Manoj et al. (2011). The other two spectra were obtained in GO 50403 *Spitzer* program (PI: Espaillat) on June 1 and 8 in 2008 and were first presented in Espaillat et al. (2011). The two General Observer (GO) observations do not show large differences between them. Therefore, in this work we only present the IRS spectrum taken on 2008 June 1.

Luhman (2004) found a spectral type of K6 for CS Cha; at that time, the binarity was not established. Using this information, Espaillat et al. (2007a) found a value for the extinction, $A_V = 0.8$, matching the $V-I$ color of the star to that of a main-sequence standard from Kenyon & Hartmann (1995). They take this value to deredden the *Spitzer* spectrum using the Mathis reddening law (Mathis 1990). We adopt the same SED in this work. A distance of $d = 160$ pc is adopted for this system (Whittet et al. 1997).

Guenther et al. (2007) found CS Cha to be a binary. They did not report the precise orbital parameters, but we use their results as reference. They found a fit with an orbital period of 2482 days with a companion of a mass larger than or equal to 0.1 $M_\odot$. Espaillat et al. (2011) take a star of 0.91 $M_\odot$ in their single star model. Using the previous restriction on the secondary mass and the value of the primary mass in the single star model, we consider two cases for the binary system: Case 1 is a set of stars with masses of 0.8 $M_\odot$ and 0.3 $M_\odot$, and Case 2 corresponds to 0.9 $M_\odot$ and 0.1 $M_\odot$ stars. For an estimated age of 2 Myr (Luhman 2004) for the system and the masses of the stars, we use the pre-main-sequence isochrones of Siess et al. (2000) to find the radius $R$, and the surface temperature $T_s$ for each star. Our choice is justified by fitting the observed flux at low wavelengths, where the contribution of the disk is very small. We decided not to increase the secondary mass value further, because in that case, the spectral type of the primary would be far from the one derived by Luhman (2004). In order to argue this, we assume that the primary spectral type is close to the estimate which takes into account just one star (Luhman 2004). A comparison between the SED of the single star used in Espaillat et al. (2011) and the addition of both star’s spectra for Cases 1 and 2 are shown in Figure 1. Finally, Espaillat et al. (2007a) estimate a mass accretion rate of $1.2 \times 10^{-8} M_\odot$ yr$^{-1}$ using the UV excess on one star, which we distribute between both stars (see Section 4.1). The parameters for both combinations of stars (Cases 1 and 2) are presented in Table 1.

## 3. THE MODEL

The basic model for CS Cha is similar to the one described in Nagel et al. (2010). In summary, it includes the emission of the inner wall of a circumbinary disk illuminated by the two stars of the binary system. It also includes the emission of optically thin dust in the inner “hole” of the disk. As noted in Espaillat et al. (2007a, 2011), the size of the hole is too large to be explained solely by the interaction of the binary with the disk. The outer regions of the circumbinary disk does not contribute at the wavelengths observed (mid-infrared), and for this reason, it is not included here (D’Alessio et al. 2005; Espaillat et al. 2007a). In principle, the emission of the wall is intrinsically variable with a period given by the orbital period of the binary system. This is because the two stars are changing their distance relative to different points on the wall. In addition, the wall has a different projected surface in the plane of the sky. However, in the case of CS Cha, the wall is located too far from the stars, according to the SED modeling conducted by Espaillat et al. (2011). Using models incorporating two stars

### Table 1

| Case | $M_1$ ($M_\odot$) | $T_1$ (K) | $R_1$ ($R_\odot$) | $M_{1.1}$ ($M_\odot$ yr$^{-1}$) | $M_2$ ($M_\odot$) | $T_2$ (K) | $R_2$ ($R_\odot$) | $M_{2.1}$ ($M_\odot$ yr$^{-1}$) |
|------|-----------------|-----------|-------------------|-------------------------------|-----------------|-----------|-------------------|-------------------------------|
| 1    | 0.8             | 4059      | 1.74              | 0.4E-8                        | 0.3             | 3313      | 1.29              | 0.8E-8                        |
| 2    | 0.9             | 4204      | 1.8               | 0.4E-8                        | 0.1             | 2998      | 0.85              | 0.8E-8                        |

*Figure 1.* Comparison between the stellar spectrum used in Espaillat et al. (2011) and in this work. For reference, the observations of CS Cha are represented with solid and pointed lines. The optical data are shown as solid squares (Gauvin & Strom 1992). The spectrum for the isolated star used in Espaillat et al. (2011) is shown as a dashed line. The long dashed and point dashed lines represent the combined spectrum obtained from both stars for Cases 1 and 2, respectively.
illuminating the wall, we found that the predicted difference in the wall emission is too small to explain the observations (1% at the 10 μm peak). As Espaillat et al. (2011), we propose that the mid-IR variability of CS Cha is due to variations in mass and illumination of optically thin dust in the circumbinary disk inner hole. We adopt a spatial distribution for this dust which is based on results of numerical simulations in the literature.

3.1. Outer Wall

We assume that the edge of the circumbinary disk is a vertical cylindrical wall illuminated by the stars. To the best of our knowledge, there are no calculations on the shape of the wall in circumbinary disks. For accretion disks around single stars, it has been proposed that the inner wall is curved, because the sublimation temperature of the dust grains depends on density (Isella & Natta 2005) and on grain size (Tannirkulam et al. 2007). However, in the case of a circumbinary disk, the inner disk truncation is produced by dynamical effects and not dust sublimation. For the case of disks with embedded planets, there are detailed calculations by Varnière et al. (2004) and Crida et al. (2006) of the surface density profile of the gap, that in principle could be used to define a shape of the inner wall. However, the cases discussed in these papers correspond to low-mass companions (planets) and it is not clear how one can scale this to binary systems. In addition, the density profile depends on viscosity, the disk aspect ratio, etc., which are unknown properties for CS Cha.

We assume that the dust in each surface element of the inner edge of the circumbinary disk is in radiative equilibrium with the impinging radiation field from the stars. The flux received at each surface element of the wall is the addition of the contributions of both stars, taking into account the geometry of the disk midplane for each surface element of the disk inner wall, and a temperature is calculated assuming radiative equilibrium, for the different distances of the stars at different orbital positions. Also, we assume that each star is accreting from a small circumstellar accretion disk that receives mass from the circumbinary disk (Günther & Kley 2002). It is usually assumed that for T Tauri stars surrounded by accretion disks, accretion shocks exist at the stellar surface that emit UV and optical radiation. We include the emission of these shocks as a source of irradiation (Muzerolle et al. 2003). The luminosity liberated in these shocks is the accretion luminosity, ..L_{acc}.., and we assume an effective temperature for the shocks of ~8000 K (Calvet & Gullbring 1998). Thus, the SED of each star is a combination of their photospheric and shock emission.

The zeroth and first moments of the radiative transfer equation are solved as in Calvet et al. (1991; see also D’Alessio et al. 2005). The irradiation flux interacts with the dust in the wall, a fraction is absorbed and another fraction is scattered. The scattered fraction produces a diffuse radiation field, which is finally absorbed at deeper layers. The transfer equation is integrated along the radial direction (parallel to the disk midplane) for each surface element of the disk inner wall, and a temperature is calculated assuming radiative equilibrium. The temperature is a function of radial optical depth. In this calculation, we assume that the density of the wall at the edge of the circumbinary disk is high enough to allow thermal equilbrium between grains of different sizes and gas. Thus, a unique temperature describes the wall’s thermal emission for each wall location.

For the calculation of the temperature on the surface of the wall \( T(\tau = 0) \), we use the optical properties of the dust at this temperature. The implicit equation for this temperature is then solved with an iterative procedure. The opacity evaluated at the wall surface temperature is used to calculate the temperature as a function of \( \tau \). Finally, with the temperature radial distribution of each wall pixel, we calculate the emergent intensity, and taking into account the geometry of the wall and occultation effects, we calculate the contribution of the wall to the SED.

3.2. Optically Thin Dust in the Inner Hole

The models of gap formation in circumbinary disks show a decrease in mass surface density between an inner hole formed due to gravitational interactions of the binary and the disk (Artymowicz & Lubow 1994) and the outer disk, which suggests the gap is optically thin. Note that planets immersed in the disk are able to increase the size of the hole (Zhu et al. 2011; Dodson-Robinson & Salyk 2011). Observations of circumbinary disks at millimeter wavelengths, which resolve the inner hole (Guilloteau et al. 1999 for GG Tau; Guilloteau et al. 2008 for HH30; Andrews et al. 2010), confirm that it has a low density and low optical depth. This is the case for transitional disks (Hughes et al. 2007 for TW Hya; Hughes et al. 2009 for GM Aur; Andrews et al. 2011). The inner hole might have optically thin dust that contributes to the near- and mid-IR SED (e.g., TW Hya, Akeson et al. 2011; Calvet et al. 2005; Espaillat et al. 2007a, 2007b, 2010).

We consider that the distribution of material inside the hole is not axisymmetric (see Section 3.2.1), following the results from simulations of the interaction between the binary system and the disk. Also, since the dust in the hole is optically thin, with very low density, we calculate a different temperature for each grain size, assuming radiative equilibrium between the grain absorption of stellar and shock radiation and emission of its own thermal radiation. Finally, we calculate the contribution to the SED of this optically thin material.

3.2.1. Dust Spatial Distribution

The gravitational interaction between the disk and the binary system sets constraints on the possible configurations of the disk material. A binary system is able to create a hole in the circumbinary disk (Lin & Papaloizou 1979; Artymowicz & Lubow 1994), because there is an inner region without stationary orbital configurations. The stable orbits for the particles are located very close to each star (circumstellar disks) and further out, in trajectories around both stars (circumbinary disk; Pichardo et al. 2005; Nagel & Pichardo 2008). As one would expect, the closer the material is to one of the stars, the less important its interaction with the other one. However, this configuration is perturbed when hydrodynamical interactions are taken into account. In this case, the material can lose angular momentum, and the resulting orbits end up connecting their point of origin in the circumbinary disk with each one of the circumstellar disks (Artymowicz & Lubow 1996; Günther & Kley 2002). In order to define a structure consistent with the results of these hydrodynamical simulations, we model the system as a circumbinary disk, two circumstellar disks and two streams of material, crossing the circumbinary disk hole, and connecting the outer circumbinary disk with the inner circumstellar disks. Note that the larger hole present in CS Cha (Espaillat et al. 2007a, 2011) cannot be explained only with the binary; thus, one requires another mechanism to produce it, perhaps another stellar mass companion or a multiple planetary system (Zhu et al. 2011; Dodson-Robinson & Salyk 2011). This will change the details of the structure in the hole, which we will not consider here.
Artymowicz & Lubow (1996) present smoothed particle hydrodynamics simulations (Monaghan 1992) which follow the material that is traveling from the circumbinary disk to the stars. They note that the accretion is modulated in time with a periodicity given by the orbital period of the binary. The simple picture is that the material in the edge of the disk is perturbed near the apocenter of the binary, but requires a time delay to fall to one of the stars, arriving around pericenter. Of course, the precise evolution depends on the mass ratio and eccentricity of the binary system (Artymowicz & Lubow 1996). A result of this is that the time of evolution of the material through the gap is of the order of the orbital period ($P = 2482$ days). This timescale is smaller than a typical dust coagulation timescale ($\sim 10^5$ years for $R \sim 10$ AU; Weidenschilling 1977; Birnstiel et al. 2010), so we assume that the grain composition and size distribution do not change during travel.

The circumbinary material in the outskirts of the disk initially evolves slowly, characterized by a viscous timescale evaluated at the radius of the circumbinary disk. Then, the material arrives to a radius defined by the gravitational interaction of the binary system with the disk (Artymowicz & Lubow 1994; Pichardo et al. 2005). Starting from this radius, the matter loses its axisymmetry and flows in two streams. The two streams are launched from two points called the saddle points. As noted in the last paragraph, the characteristic time for the evolution of the material in the gap is of the order of the binary orbital period. Thus, when the material arrives at the saddle points, it moves toward the inner circumstellar disks within a dynamical timescale.

The saddle points are analogous to the Lagrangian points in the three-body circular restricted problem in classical mechanics (Murray & Dermott 1999). For a circular binary, one can define a rotating coordinate system where the stars are at rest. Thus, there is a constant of motion, the Jacobi constant, and specifically two linear Lagrangian points (Murray & Dermott 1999), that define the locus where material with enough value for this constant is able to move from orbits around the binary system to orbits connecting the circumbinary disk with circumstellar disks. In order to extend the analogy to an eccentric system, we note that the gravitational potential can be expanded as an infinite sum of terms. In many cases, one can describe the potential with only a few of them. For an eccentric binary system, the potential can be simplified using the terms $(m, l) = (0, 0)$ and $(m, l) = (2, 1)$ of its expansion (Artymowicz & Lubow 1994). Moreover, this potential rotates at a rate $\Omega_b/2$, where $\Omega_b$ is the mean angular velocity of the binary. For this simplified case, two points can be defined (the corresponding Lagrangian points), which corotate with the potential. These are the launching points for the streams mentioned in the last paragraph, i.e., the saddle points. Analogous to the circular case, the material that accretes from the external regions of the disk is able to cross the radius where the saddle points are located, primarily at these locations.

The saddle points are located at a radius $R_s = 1.587 a$, where $a$ is the semimajor axis. Thus, we can conclude that at larger radii, the orbital backbone of the material orbits around the binary system (Pichardo et al. 2005). At smaller radii the material is located in two streams starting at the saddle points (Artymowicz & Lubow 1996; Günther & Kley 2002) and ending in the inner disks.

The configuration used in this work, which is consistent with the orbital restrictions given by the binary system presence, is a ring of material between $R_s$ and $R_{\text{wall}}$, where $R_{\text{wall}}$ is the position of the inner edge of the outer disk. At $R < R_s$, the material is located in the streams that connect the circumbinary and circumstellar disks. This is shown schematically in Figure 2. The ring corresponds to a region where the material evolves viscously, because this is consistent with the gravitational disk–stars interaction as described previously. The difference between this and the actual outer disk is that the ring is optically thin. As we mentioned above, in the case of CS Cha, for which we have Spitzer mid-IR fluxes, we do not include the contribution of the circumbinary disk to the SED, because it is too cold to emit in this wavelength range (Espaillat et al. 2007a, 2011). Also, we assume that the circumstellar disks, streams, and outer ring are all optically thin.

### 3.2.2. Dust Temperature

We assume that the optically thin dust in the inner hole is in thermal equilibrium with the stellar radiation. However, the density in the gap is so low, that thermal equilibrium between gas and dust grains is not expected. Therefore, each grain with a different size would have a different temperature.

The critical gas density for thermal equilibrium between dust grains and gas can be estimated by assuming that the collisional timescale is equal to the thermal timescale (e.g., Chiang & Goldreich 1997; Glassgold et al. 2004). The collisional timescale is given by

$$\tau_{\text{col}} = \frac{1}{n_H \bar{v} \pi a^2},$$

where $n_H$ is the number density of the molecular hydrogen, $\bar{v}$ is the mean velocity of a molecule, and $a$ is the radius of the grain. We consider that the velocity is thermal, however, it is possible that there is a turbulent component, which amounts to a fraction of this velocity. Using the fact that the typical velocity associated with turbulence in the $\alpha$-parameterization of the viscosity (Shakura & Sunyaev 1973) in protoplanetary disks (Hawley et al. 1995) is around $0.01$ of the sound speed, we can conclude that including the turbulent velocity does not change our following conclusions. The thermal timescale can be estimated as the time that a particle of dust takes to radiate...
all its thermal energy at temperature $T_d(a)$,

$$\tau_{\text{ther}} = \frac{kT_d(a)}{4\pi a^2 \sigma_{SB} T_d(a)^4},$$

where $k$ is the Boltzmann constant and $\sigma_{SB}$ is the Stefan–Boltzmann constant.

Thus, the critical density is (Glassgold et al. 2004)

$$n_{\text{cr}} = \frac{4\sigma_{SB} T_d(a)^3}{k \bar{v}},$$

and substituting typical numerical values, it can be written as

$$n_{\text{cr}} = (1.133 \times 10^8 \text{ cm}^{-3}) \frac{T_d^3}{T_d^{2.7}},$$

where $T_d$ is the gas temperature.

Next, we would estimate the gas density associated with the optically thin material to compare it with this critical density. If we assume $T_d \approx T_a$, and take $T_d \approx 100$ K as characteristic of the streams, then $n_{\text{cr}} = 3.34 \times 10^{-11} \text{ g cm}^{-3}$. Note that a change in $T_d$ of an order of magnitude corresponds to a factor of three change in $n_{\text{cr}}$ (see Equation (4)), which does not modify our conclusions.

In order to get an order of magnitude for the density in the streams, we note that the area covered by the streams is around $0.1\pi R_i^2$ (Artymowicz & Lubow 1996). We assume that the material falls from the inner edge of the ring toward the star in a few times the free-fall time, which is 1.5 years. This is consistent with the fact that in Artymowicz & Lubow (1996), the streams change on the order of an orbital period of the binary, $T_{\text{orb}} \sim 7$ years. Thus, according to a mass accretion rate of $M = 10^{-8} M_\odot$ yr$^{-1}$ (Espaillat et al. 2007a), the mass in the streams should be around $7 \times 10^{-8} M_\odot$. Note that in the hydrodynamical simulations of a disk around a binary system, Günther & Kley (2002) assume a typical height in terms of the radius $R$ in the disk, without dependence on the azimuthal angle, which is given by

$$H(R) = \left(\sum_{i=1,2} \frac{GM_i}{c_s^2 |R - R_i|^3}\right)^{-1/2},$$

where $G$ is the gravitational constant, $M_i$ is the mass of each of the stars, $c_s$ is the sound speed, and finally $R_i$ is the distance of each star with respect to the origin. For Case 1 and using a typical temperature of 100 K for molecular hydrogen and $|R - R_i| = R_s$, $H(R) = 0.049 R_s$. Thus, a typical value for $H$ is 0.1 $R_s$, which we consider here. Differences in $H$ do not change the following conclusions.

Given the mass in the streams, the area covered and the height calculated previously, the characteristic density in the streams is around $n_{\text{str}} = 10^{-14} \text{ g cm}^{-3}$, which means that $n_{\text{str}} \ll n_{\text{cr}}$. This implies that the gas and the dust grains are not in thermal equilibrium, and since the absorption coefficient of the grains depends on grain size, $a$ grains with different sizes have different temperatures, $T(a)$.

We divide the grain sizes into 100 bins equally spaced in log$(a)$ between $a_{\text{min}} = 0.005 \mu$m and $a_{\text{max}} = 4 \mu$m, distributed with a power-law profile with exponent $p = -3.5$. We take this value of $a_{\text{max}}$ according to the detailed modeling of Espaillat et al. (2011). For each size, we calculate the temperature from radiative equilibrium between the energy of the stellar and shock radiation absorbed by the grain and the energy lost by radiation. As expected, the temperature of the smallest grains is higher than the temperature of the larger grains (see discussion in Section 5.2 and Figure 3). We also estimate a mean temperature, as a unique temperature for the whole grain distribution, assuming the grains have a Mathis–Rumpl–Nordsieck (MRN) power-law size distribution, and use this temperature as a reference. This temperature is also calculated assuming radiative equilibrium with the radiation fields of the stars and their accretion shocks, but using mean absorption coefficients. As expected, at the same position in space, the temperature of the smallest grains is higher and the temperature of the larger grains is lower than this mean temperature, due to a higher heating efficiency. Figure 3 illustrates this by showing temperature versus distance in the primary’s stream (Case 1, GO observations) for the smallest grain (0.005 $\mu$m), the largest grain (4 $\mu$m), and for a power-law distribution of grain sizes between 0.005 $\mu$m and 4 $\mu$m.

Remember that the estimation of the temperature is done for all the locations where there is material, and in each case the temperature of each grain size is calculated. The grain composition adopted here is amorphous olivine, consistent with Espaillat et al. (2011), where 95% is olivine and 5% is crystalline silicates. In addition, we include organics and troilite. The abundances are $\zeta_{\text{sil}} = 0.0034$, $\zeta_{\text{org}} = 0.001$, and $\zeta_{\text{troi}} = 0.000768$, for silicates, organics, and troilite, respectively.

4. PARAMETERS

Since there are many input model parameters, we search for observational and theoretical constraints for some of them. In the next sections, we describe the fixed and free model parameters.

4.1. Fixed Parameters

For the best model for CS Cha in Espaillat et al. (2007a) and Espaillat et al. (2011), the inner edge of the circumbinary disk,
which we refer to as the “wall,” is located at $R_{\text{wall}} = 43$ AU and $R_{\text{wall}} = 38$ AU, respectively. The difference found in $R_{\text{wall}}$ for CS Cha was due to using different dust opacities. The models of Espaillat et al. (2011) use a different distribution of silicates with respect to the models for CS Cha in Espaillat et al. (2007a). In the first modeling, 60% of the dust is silicates compared with 88% in the other case. For both cases, crystalline silicates correspond to a small amount. Here we use the most recent value, $R_{\text{wall}} = 38$ AU, because it corresponds to a better fit of the 10 μm band. At such a large distance, there is almost no difference between a model with one star and a model with two stars, because $a \ll R_{\text{wall}}$ ($a = 3.703$ AU for Case 1, $a = 3.587$ AU for Case 2). Thus, it is safe to assume the wall parameters to be the same inferred by Espaillat et al. (2011), including the wall height ($h = 7$ AU) and the inclination angle between the disk axis and the line of sight ($i = 60^\circ$).

As noted in Section 2, we fix the value estimated by Espaillat et al. (2007a) for the mass accretion rate at $1.2 \times 10^{-8} M_{\odot}$ yr$^{-1}$. We distributed this value, $0.4 \times 10^{-8} M_{\odot}$ yr$^{-1}$ and $0.8 \times 10^{-8} M_{\odot}$ yr$^{-1}$, for the primary and secondary, respectively. This is in agreement with Artymowicz & Lubow (1996), where the simulations with $e = 0.1$ show that the mass accretion rate to the secondary is a factor of two larger than the mass accretion rate to the primary star. Notice that the accretion luminosities are an order of magnitude lower than the star luminosity. As a result, we expect that the precise value of the former does not make a substantial difference in the resulting SED. The stellar parameters for Cases 1 and 2 are summarized in Table 1.

The streams start at the saddle points of the simplified potential (Artymowicz & Lubow 1996; see Section 3.2.1) and end at each circumstellar disk. For simplicity, their shape is a line that connects both positions. Although the thickness of the streams is a free parameter, one condition should be held: the flows fill around 10% of the surface of the hole (Artymowicz & Lubow 1996). Following the simulations of Artymowicz & Lubow (1996), we can safely assume that the density of streams and the outer ring are one tenth of the values associated with the compact circumstellar disks. We assume that both disks have a minimum radius of $R_{\text{min}} = 0.1$ AU and a maximum radius of $R_{\text{max}} = 0.5$ AU. As we mentioned above, the mass accretion rate to the secondary is about two times the value associated with the primary following Artymowicz & Lubow (1996, see also Bate 2000). For the modeling, we translate this as a condition on the filling factor inside the hole associated with each stream. Thus, we assume that the area occupied by the primary star stream is half the area of the stream reaching the secondary. The last requirement consistent with Artymowicz & Lubow (1996) is that the mass from the circumbinary disk that falls into any of the streams at apocenter is around twice the value at pericenter. Finally, in order to characterize the mass of the streams for every orbital location, we modulated the area of the streams (equivalently the mass) with a sinusoidal function in the azimuthal angle. The advantage of using this information to define the stream structure is that their geometrical parameters are fixed. The density on each stream is constant, and it is fixed using the fit for the observed spectrum (see Section 5).

### 4.2. Free Parameters

The eccentricity is a parameter that is not restricted by the observations of Guenther et al. (2007). Artymowicz & Lubow (1996) point out that the variability of the stream mass depends on the eccentricity. The amount of material associated with the streams depends on the distance of the stars to the wall at apocenter, and this strongly depends on the eccentricity. Note that for a circular binary, the minimum distance of each star to the disk does not change for the axisymmetric wall; thus, the structure is stationary and there is no variability in the amount of material in the hole. Thus, in order to explain the variability, the system must be eccentric. Also, the observed SED variations suggest significant changes in the amount of material in the streams (17% according to Espaillat et al. 2011). For the modeling, in order to look for a best fit we take two values for the eccentricity, $e = 0.1$ and $e = 0.2$.

The remaining parameter needed to fully characterize the binary system is $\phi$. It is the angular position of the stars along the orbit at the time we are observing the system: $\phi = 0.5 \pi$ corresponding to pericenter and $\phi = 1.5 \pi$ to apocenter. The values we try in order to find the best fit for the earlier observation are $\phi_1 = (0.0, 0.5, 1.0, 1.5) \pi$. The set of models tried is shown in Table 2. The second epoch corresponds to $\phi_2$, constrained by the time elapsed between the two observations, i.e., 1065 days. We solve the equations of motion of the binary system, looking for configurations separated by this time.

Finally, the dust mass surface density for the region assigned to the streams is a free parameter. The density is increased from zero until the flux level in the SED is reached.

### 5. RESULTS

We calculate models at some representative points on the parameter space, as given in Section 4.2. For each pair of central stars (Case 1 and Case 2) and each pair of values ($e, \phi_1$), we calculate an SED adding the contributions of the stars, the wall, and the optically thin dust, scaled by the dust mass surface density. The synthetic and observed SEDs are subtracted, and we calculate their corresponding $\chi^2$. The mass surface density in each epoch is taken to be the one that minimizes $\chi^2$.

#### 5.1. Fitting the SED

The fit is done independently for both epochs. In order to find the best-fitting model, we search for the model that minimizes $\chi^2$. Because this is a small set of the parameter space, we cannot claim that we find a unique model. Due to the large number of assumptions and unknowns (for example, the exact configuration of the streams), degeneracy of the SED fitting is expected. Thus, one can only claim that we find models consistent with the observations.
Figure 4. Best fit for CS Cha for Cases 1 (left panel) and 2 (right panel; see Table 1) for the GTO observation in 2005. The solid line is the SED observation. The pointed line is the hole SED for the model. The dashed line corresponds to the wall flux. The addition of both stellar SEDs are represented with a point-long-dashed line. Finally, the small-long-dashed line is the total flux for the models.

Figure 5. Best fit for CS Cha for Cases 1 (left panel) and 2 (right panel; see Table 1) for the GO observation on 2008. The lines have the same meaning as Figure 4.
Figure 6. Diagram of the structure of the streams viewed pole on, for the best fit for the Case 1 (see Table 1) for the GTO observation (upper plot) and the GO observation (lower plot). The observer is at an inclination of 60°. The crosses (+) represent the primary star and the rotated crosses (×) represent the secondary star. The region inside both lines corresponds to the material associated with the streams. The circumstellar disks are drawn and the label “X” refers to the saddle points, where the streams are launched. The surrounding circle represents the inner boundary of the optically thin ring of material.

The fit for the GTO observation in 2005 is shown in Figure 4 for Cases 1 and 2. The fit for the GO observation in 2008 is shown in Figure 5, also for both cases. The parameters for the best-fit model for Cases 1 and 2 are the same, this is $e = 0.1$ and $\phi = (0.5, 1.38)\pi$. The shape of the streams’ structure for the fit is shown in Figure 6 for Case 1, compared to the GTO and GO observation of CS Cha. The streams for Case 2 are almost identical to the ones for Case 1, thus, we do not show them here.

5.2. Fitting the Observed Variability

The fit in the last section is done for both epochs, but consistently taking into account the time difference between the observations. Thus, the variability can be explained with the previous fits. In Figure 7, we show the Case 1 SED fits for both observations, which were previously presented in Figures 4 and 5. Figure 8 is the same but for Case 2, showing the fits also presented in Figures 4 and 5. We note that the best fit for either model with $e = 0.1$ or $e = 0.2$ is $\phi_1 = 0.5$. In order to check this tendency for every $e$, we ran models for $e = 0.5$ and $e = 0.9$. The tendency is corroborated, but the best models according to $\chi^2$ are worst for larger $e$. We ran models for $e = 0.1$ for other values of $\phi_1$, such that the whole set is $\phi_1 = (0.0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75)$. Even for this larger set, the best fit is found for $\phi = 0.5$. 

Figure 7. Modeled variability for CS Cha for the Case 1 (see Table 1). The solid lines represent the SED for the GTO observation (2005) and the GO observation (2008). The dashed and the pointed lines are the modeled SED for both epochs. These correspond to the models shown in Figures 4 and 5.

Figure 8. Modeled variability for CS Cha for the Case 2 (see Table 1). The solid lines represent the SED for the GTO observation (2005) and the GO observation (2008). The dashed and the pointed lines are the modeled SED for both epochs. These correspond to the models shown in Figures 4 and 5.
Given the observational constraints and the properties we have fixed for the inner wall based on our previous modeling (Espaillat et al. 2011), we find that any eccentricity that satisfies \( e > 0 \) and \( \phi_1 \) around 0.5 produces a configuration consistent with the observed SEDs in the two epochs. This means that the eccentricity \( e \) is not constrained by our models and it appears that only observations of the detailed orbit of the binary system would allow us to quantify this parameter.

The SEDs of the present models (for both, Case 1 and Case 2) are similar to the SED of a single star model presented by Espaillat et al. (2011). In the single star model the SED variation is related to a change in the mass of the optically thin dust in the inner hole. In the present model with two central stars, we also consider a change in dust mass, but besides this there is a source of variability given by the change in illumination produced by the stars, which is absent in a single star model.

As we show, the variability can be explained by the differences for each orbital configuration of the binary system, in the illumination of the material in the circumstellar disks and streams. Also the amount and the geometrical configuration of the dust is important in terms of the orbital configuration. A visualization of this effect is given in Figure 9, where for the Case 1 fit, the intensity for a wavelength of 10 \( \mu \text{m} \) is presented. One can clearly see that the contribution to the emission is larger for the configuration associated with the GO observation (Figure 6). Notice that in Figure 9, the variation in area for the streams means a larger amount of mass, and the gray scale corresponds to changes in the illumination.

The associated dust mass in circumstellar disks and streams is around \( 10^{-12} M_\odot \), of the same order of the estimate by Espaillat et al. (2011), where the material was located only in one circumstellar disk. The dust surface density on each stream is uniform and can be calculated with the total mass of dust and the area associated with each stream. In Table 3, we present the dust surface density for the primary and the secondary streams, for Cases 1 and 2, and for the configurations associated with both epochs. In order to estimate from the model a mass accretion rate we do the following. We assume that the gas attached to the dust in the disks and streams is responsible for the mass accretion rate estimated in Espaillat et al. (2007a). Using the dust abundances, the mass of gas is of the order of \( 10^{-10} M_\odot \), if we now use a free-fall time from the saddle point as the fastest time for the accretion, the mass accretion rate is around \( 10^{-10} M_\odot \text{ yr}^{-1} \). This value is two orders of magnitude smaller than the estimate in Espaillat et al. (2007a). A possible explanation for this is that the dust-to-gas ratio is lower than usually expected. A way to do this is through a filtering effect in the inner edge of the circumbinary disk. Rice et al. (2006) note that the pressure gradient in this location acts as a filter, only allowing small dust grains to trespass it, holding the larger ones. However, the typical critical size is around 10 \( \mu \text{m} \), which is larger than the maximum value taken in our work, \( \theta_{\text{max}} = 4 \mu \text{m} \).

Another idea is that the mass accretion rate inferred from the \( U \)-band excess has uncertainties due to the estimation process in itself and due to the fact that the system is a binary. An improvement of this estimate requires a detailed description of the evolution of the particles (solid and gaseous), since they leave the inner edge of the circumbinary disk to finally accrete at one of the stars (Günther & Kley 2002). Note that a \( U \)-band excess is not always indicative of accretion, because one has to check the shape of the lines profiles to safely assume that the system is accreting (Ingleby et al. 2011). However, a complete study able to elucidate the dynamics of the hole material is beyond the scope of this paper.

In previous works (D’Alessio et al. 2005; Nagel et al. 2010; Espaillat et al. 2011), the dust temperature in the hole and the emissivity are grain-size-mean values calculated using an opacity, given by the average opacity over the grain size distribution. In here, since the dust in the hole has such a low density and cannot be considered in thermal equilibrium with the gas (see Section 3.2.2; Chiang & Goldreich 1997; Glassgold et al. 2004), we calculate a dust temperature and emissivity as a function of grain radii. For the sake of evaluating the differences between both approaches, we calculate a model with the grain-size-mean opacity to fit the SED. We find that the resulting SEDs are very similar, but for the model with the grain-size-mean opacity assumption, the mass of the optically thin material is 19% of the mass of the models where no thermal equilibrium is assumed. This difference between both approaches means that it is worthwhile to do the proper estimate.

### Table 3

| Case | Epoch | Stream to | \( \Sigma \) (g cm\(^{-2}\)) |
|------|-------|-----------|------------------|
| 1    | GTO   | Primary   | 1.76E-5           |
| 2    | GTO   | Secondary | 1.92E-5           |
| 3    | GO    | Primary   | 1.58E-5           |
| 4    | GO    | Secondary | 1.45E-5           |
| 5    | GO    | Primary   | 1.91E-5           |
| 6    | GO    | Secondary | 4.05E-5           |
| 7    | GO    | Primary   | 2.85E-5           |
| 8    | GO    | Secondary | 1.43E-5           |

### 6. SUMMARY AND CONCLUSIONS

We have shown that the \textit{Spitzer} IRS spectrum of the binary CS Cha is consistent with the emission from the inner disk structure generated by the double system. This is a step forward with respect to the modeling in Espaillat et al. (2011), because we include the binary system and more details about the hole dust configuration. The presence of a binary means that the disk is gravitationally truncated, forming an inner edge (wall) which is directly illuminated by the stars. This would be a good candidate to follow up for millimeter imaging to confirm the hole size.

As already discussed by Espaillat et al. (2011), the mid-IR variability of CS Cha is restricted to the 10 \( \mu \text{m} \) silicate...
band. This implies that it is not produced by the variable illumination of the wall, which has a large radius as inferred from SED fitting, but by variations in the emission of optically thin dust in the inner hole of the circumbinary disk. We adopt a mass distribution inside the hole consistent with dynamical simulations (see next paragraph), i.e., the optically thin dust is located in a ring, two streams and two circumstellar disks. The mass of the streams is modulated by the orbital configuration of the stars, which combined with a variable illumination from both stars, can explain the observed variability for a reasonable set of parameters.

The distribution of the material in the hole is consistent with the dynamical restrictions due to the presence of a binary system (Artymowicz & Lubow 1994; Pichardo et al. 2005). The material is located in a ring, streams and circumstellar disks (see Section 3.2.1). This configuration is able to explain the observed variability. An SED fit is done for the optically thick regime using hydrodynamical simulations of the formation and evolution of the hole material in a circumbinary disk in Günther & Kley (2002) and Günther et al. (2004). de Val-Borro et al. (2011) do similar simulations for the close binaries V4046 Sgr and DQ Tau, aiming to explain the shape variability of gas lines. In this case, the density of the structure points to the optically thick regime. Thus, it is important to point out that for the first time (as far as we know), the SED fitting of the mid-infrared variability, for the emission of optically thin material inside the hole of a circumbinary disk, using a configuration consistent with the theory and simulations is successfully done.

The masses for the estimated optically thin dust are of the same order of magnitude as the values estimated in Espaillat et al. (2011), however, note that the configurations of the material in the gap are quite different between both cases. Given the unknowns, we decide to calculate a small set of models in order to illustrate that they can explain the observed SEDs and variability, but we do not claim that these models are unique. However, new observations of this system will be able to increase the constraints, for a more extensive testing of our model. In the future, this model will be tested for more binary stars with multiple observations in the infrared. Unfortunately, by now the cryogenic mission on board the Spitzer Space Telescope is over. The ongoing warm mission is just able to confidently see at the smaller range of wavelengths. Thus, we require the launching of the James Webb Space Telescope to pursue this project further. The interferometer ALMA can see at a wavelength (330 μm) which is at least an order of magnitude larger than the Spitzer wavelength window. At this frequency, Wolf & D’Angelo (2005) study simulation images of a planet embedded in a protoplanetary disk. They conclude that the planet with an accretion luminosity of 10^{-5} L_\odot is able to perturb the disk in order to be detected by ALMA. In our case, the ratio of the emission from the stellar peak and the estimated emission at 330 μm is around 10^5, thus, we think that the streams can barely be seen with ALMA.

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