THE INNER RADIUS OF T TAU RI DISKS ESTIMATED FROM NEAR-INFRARED INTERFEROMETRY: THE IMPORTANCE OF SCATTERED LIGHT

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Received 2007 October 29; accepted 2007 November 30; published 2008 January 8

ABSTRACT

For young Herbig Ae/Be stars, near-infrared interferometric measurements have revealed a correlation between the luminosity of the central object and the position of the disk inner rim. This correlation breaks down for the cooler T Tauri stars, a fact often interpreted in terms of disks with larger inner radii. In most cases, the conversion between the observed interferometric visibility and the calculated disk inner radius was done with a crude disk emission model. Here we examine how the use of models that neglect scattered light can lead to an overestimation of the disk sizes. To do so, synthetic disk images (and visibilities) are calculated with a full treatment of the radiative transfer. The relative contributions of thermal emission and scattered light are compared. We find that the latter cannot be neglected for cool stars. For further comparison, the model visibilities are also converted into inner disk radii using the same simple disk models as found in the literature. We find that reliable inner radii can only be estimated for Herbig Ae/Be stars with these models. However, they lead to a systematic overestimation of the disk size, by a factor of 2–3, for T Tauri stars. We suggest that including scattered light in the models is a simple (and sufficient) explanation of the current interferometric measurements of T Tauri stars.

Subject headings: planetary systems: protoplanetary disks — radiative transfer — scattering — techniques: interferometric

Online material: color figures

1. INTRODUCTION

Near-infrared (NIR) broadband interferometric observations of young stellar objects trace the inner part of the warm dusty circumstellar environment (≤1 AU) and can be used to constrain its physical properties and to characterize the size and location of the emitting region.

The NIR sizes, derived from simple geometrical models, are found to be consistent with the dust sublimation radius for Herbig Ae and late Be objects (Monnier & Millan-Gabet 2002; Millan-Gabet et al. 2007 and references therein). Interestingly, observations of T Tauri stars reveal lower NIR visibilities (hereafter $V^2$). They correspond to sizes larger than the dust sublimation radii when the same simple geometrical models are used (Akeson et al. 2005b; Eisner et al. 2005, 2007). Various explanations are proposed to account for these surprisingly low $V^2$ (or large inner radii): extra heating from accretion, lower dust sublimation temperatures, small dust grains, and photoevaporation. As noted by Eisner et al. (2007) it is unlikely however that any of these mechanisms can explain by itself the large inner radii observed in all low-mass T Tauri stars. Instead, Eisner et al. (2007) favor the explanation where the inner disk’s position is controlled by the stellar magnetospheric pressure, in this case pushing the disk outward when accretion rates are low enough.

In this Letter, we explore the possibility that the position of the inner disk is incorrectly estimated, especially for T Tauri stars, because the radiative transfer (hereafter RT) schemes used are incomplete, namely that the contribution from scattering is overlooked. Scattered light is a spatially extended component potentially leading to lower $V^2$ and, by way of consequence, to a biased estimation of characteristic sizes when neglected. In the following, we investigate these effects, using detailed RT modeling, by comparing the spatial distribution of scattered light and thermal emission.

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Table 1: Optical Properties at 2.2 μm

| Composition  | \(a_{max}\) (μm) | Albedo | \(g^a\) |
|--------------|------------------|--------|--------|
| A .......... | Silicates (1) 1 μm | 0.90 | 0.53 |
| B .......... | Silicates (1) 1 mm | 0.80 | 0.62 |
| C .......... | Si + C (2) 1 μm | 0.37 | 0.58 |
| D .......... | Si + C (2) 1 mm | 0.62 | 0.91 |

\(^a\) Asymmetry parameter \(g = (\cos \theta)\) with \(\theta\) the scattering angle.

References. — (1) Dorschner et al. 1995; (2) Mathis & Whiffen 1989.

3. RESULTS

3.1. Brightness Profiles

In this section we present the cumulative fluxes, integrated in a circular aperture, as a function of distance from the star. Each contribution, i.e., direct and scattered starlight and direct and scattered thermal emission from the disk, is plotted separately for comparison. Two models (\(T_{eff} = 10,000\)K, top panel, and \(T_{eff} = 4000\) K, bottom panel) are presented in Figure 1.

For the \(T_{eff} = 10,000\) K model, the sublimation radius is located at 0.40 AU from the star (3 mas at 140 pc). Because the disk is warm, the thermal emission is of the same order as the stellar emission at \(K\) band. All contributions (except the photosphere) show similar radial profiles. Because the disk is optically thick, the dominant contribution is the scattered thermal emission from the disk, i.e., the photons coming from deep inside the disk that had to scatter before reaching the surface. Depending on radius, this contribution is as large as 2.5 times the direct disk emission in \(K\) band because the emission volume is larger. This contribution is often neglected. Within a 50 mas field of view, direct starlight is the next contributor to the total flux, followed by direct thermal emission from the disk. The scattered starlight contributes significantly less, of the order of a few percent of the stellar flux. It is only a small fraction of the direct starlight because the stellar photosphere is seen directly and the disk is geometrically thin.

For the cooler star, the sublimation radius is located closer to the photosphere, down to 0.34 mas (0.048 AU). It is only marginally resolved by current interferometers. In this case, contrarily to the more massive star, scattered starlight is of the same order as thermal emission. It can even dominate at larger distances from...
As shown in § 3.1, scattering can contribute significantly to the circumstellar flux, even at small scales. To evaluate the incidence of neglecting scattering in the interpretation of $V^2$, we compare two $V^2$ curves in Figure 2: (1) a direct Fourier transform of the images obtained through the MCFOST calculations (solid line), and (2) a Fourier transform of the image without any scattered light and where the thermal emission is scaled to the total infrared excess to compensate. This is as if all the total disk emission flux decreases faster with radius than scattered light, the integrated thermal emission curve increases more slowly than both scattered components (photospheric and disk thermal). A significant effect of scattered light on $V^2$ is therefore expected.

### 3.2. Visibilities

As shown in § 3.1, scattering can contribute significantly to the circumstellar flux, even at small scales. To evaluate the incidence of neglecting scattering in the interpretation of $V^2$, we compare two $V^2$ curves in Figure 2: (1) a direct Fourier transform of the images obtained through the MCFOST calculations (solid line), and (2) a Fourier transform of the image without any scattered light and where the thermal emission is scaled to the total infrared excess to compensate. This is as if all the total disk emission flux decreases faster with radius than scattered light, the integrated thermal emission curve increases more slowly than both scattered components (photospheric and disk thermal). A significant effect of scattered light on $V^2$ is therefore expected.

### 3.3. Estimation of Inner Radii from NIR Visibilities

The decrease of $V^2$ at short baselines due to the larger spatial extent of scattered light can result in an overestimation of the inner radius of the disk if interpreted in the wrong context. To quantify this effect, we fit the $V^2$ calculated above with a simple geometrical model composed of an unresolved point source surrounded by a thin ring, as done, e.g., by Akeson et al. (2005b) and Eisner et al. (2005, 2007). We adopt a Gaussian brightness profile in the radial direction. The contribution (flux) of the ring is set to the total contribution (excess) from the disk (i.e., thermal emission + scattered light). As the models have been calculated for pole-on disks, we restrict the study to circular rings. Fitting is performed on $V^2$ point at a baseline of 80 m (the average projected baseline in the observations of Akeson et al. 2005b) and the resulting $V^2$ curves are shown in Figure 2 (dot-dashed lines).

For the $T_{\text{eff}} = 10,000$ K star, this curve remains close to the $V^2$ curve calculated with full RT, indicating that the derived radius (0.42 AU) is a good estimation of the actual inner radius (0.40 AU). However, at short baselines the shape of the curves differ significantly, with differences larger than 10% for a 20 m baseline. Therefore, for warm stars, results from short baseline measurements should be taken with caution since they can be biased by extended emission (scattering). Interestingly, such a decrease of $V^2$ at short baselines has been observed for a few objects with IOTA (Monnier et al. 2006). Similarly, results from longer base-
lines and more distant objects (i.e., sampling the same spatial scales as described here) should also be interpreted with care.

For the cooler $T_{\text{eff}} = 4000$ K star the situation is worse. The $V^2$ curve fitted with a ring is no longer a good approximation of the true disk $V^2$ curve because of very different behavior at short baselines. The inferred ring radius (0.12 AU) is in that case a large overestimation of the actual inner radius of the disk (0.048 AU).

Figure 3 shows the derived ring size as a function of the stellar luminosity (solid line), compared to the true sublimation radius (dashed line). When neglecting scattered light, the ring size is always an overestimation of the actual inner disk radius and this overestimation increases as the temperature of the central object decreases.

Radii estimated with ring models fitted on Keck interferometer observations are overplotted on Figure 3. The selected sources are CTTS and Herbig stars at a distance close to 140 pc and have been observed in $K$ band (Table 2). Interestingly, the location of the fitted inner radii mimics very well the distribution of data points. Therefore, the contribution of scattered light appears as a simple and sufficient explanation of the observed trend of lower $V^2$ seen in late-type PMS stars given the current error bars on the measurements.

Not all data in the literature were obtained with the same instrument, however. To estimate the effect of the interferometer’s field of view, we plot on Figure 3 the derived ring size for a field of view of 1", valid for the Palomar Testbed Interferometer, for instance. As expected, the impact of scattered light is more pronounced, with a derived radius of 0.14 AU for $T_{\text{eff}} = 4000$ K, and is increasing with decreasing stellar temperature. However, because the brightness of scattered light decreases rapidly with distance from the star, the effect remains limited and significantly smaller than the one resulting from the contribution inside the inner 50 mas.

### 3.4. Effect of Dust Properties

In order to test the dependence of the findings presented in § 3.3 on dust properties, Figure 4 shows the derived radii for several dust populations. The general behavior remains unchanged and the effect of scattered light on $V^2$ is significant for all dust populations we treated.

However, finer differences may be linked to the dust properties. First, the position of the inner rim depends on the dust properties. The effect is to shift the curves vertically on Figure 4. Smaller grains and silicates are more efficiently heated and the corresponding sublimation radius is increased. Similarly, different materials with smaller sublimation temperatures also result in larger inner radii. Second, because of different scattering properties (albedo and phase function), the fraction of scattered light is larger for silicates grains, and so is the ratio of the measured radius over the actual inner radius.

Silicate dust, models A and B, provides a good match to the data, although we have not explored all possibilities. Intermediate dust properties should also agree with the data points. Moreover, with the density structure we adopted, resulting in very opaque central regions, a sublimation temperature of 1500 K yields inner radii that are too large to reproduce the observed trend at high luminosity (shaded region).

Interestingly, detailed modeling of PTI interferometric observations has been performed by Akeson et al. (2005a) including light scattering. The authors concluded that RT models have radii similar to those of geometrical models. They use dust properties with an albedo of 0.5, $g = 0.6$ (intermediate to our dust properties C and D), and $T_{\text{eff}} = 1600$ K, and their less luminous source (DR Tau) has a luminosity of 0.87 $L_\odot$. With similar parameters, we do indeed find that the overestimation of the inner radius remains limited (about 30%–40%), in agreement with the results of Akeson et al. (2005a), who found a difference of ≈30% for DR Tau between RT and ring models (see triangles and circles in Fig. 4). Unfortunately, this result was used as a validation for all sources. Should they have used different dust properties or considered lower luminosity sources, the discrepancy between the two methods would have been more striking. Because the effect of scattered light is systematic (always a decrease of $V^2$) and always larger than 30% with respect to ring models, i.e., larger than observational error bars, we suggest that scattered light should always be included in the analysis of NIR $V^2$: the cooler the object the more needed scattered light is.

### 4. CONCLUSIONS

We have investigated the effect of a complete treatment of RT in the interpretation of $V^2$. We find scattered light is an important contribution to the disk excess and dominates for low-luminosity/cool objects. In particular, we have shown this contribution to lead to a systematic decrease of the observed $V^2$. Interpreted in the wrong context, the lower $V^2$ can be mistaken with disks of larger inner radii. For more luminous objects ($>20 L_\odot$), the effect becomes significant only at short baselines (<20 m), but care must also be taken.

Depending on the adopted dust properties, part, if not all, of the observed trend of estimated large radii of late-type objects can be explained by the contribution of scattered light, without requiring any other mechanism than dust sublimation to truncate the inner disk.

However, there are several issues to consider to estimate quantitatively the exact position of the inner boundary of a given disk. The dust properties have an impact on the actual location of the disk sublimation radius and on the fraction of scattered light sent to the observer. Since the dust properties are not known accurately, the position of the sublimation radius remains slightly uncertain. Additional effects, such as viscous heating as part of the accretion process for example, might also lead to a different disk temperature profile, hence to a different emission profile. A more detailed case-by-case modeling effort together with additional constraints from other observations, such as mid-infrared spectroscopy or spectro-interferometry, should be of great help to overcome these degeneracies.

### REFERENCES

Akeson, R. L., et al. 2005a, ApJ, 622, 440
———. 2005b, ApJ, 635, 1173
Dorschner, J., et al. 1995, A&A, 300, 503
Eisner, J. A., et al. 2005, ApJ, 623, 952
———. 2007, ApJ, 669, 1072
Mathis, J. S., & Whiffen, G. 1989, ApJ, 341, 808
Millan-Gabet, R., et al. 2007, in Protostars and Planets V, ed. B. Reipurth et al. (Tucson: Univ. Arizona Press), 539
Monnier, J. D., & Millan-Gabet, R. 2002, ApJ, 579, 694
Monnier, J. D., et al. 2005, ApJ, 624, 832
———. 2006, ApJ, 647, 444
Pinte, C., et al. 2006, A&A, 459, 797
———. 2007, A&A, 469, 963