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Feasibility of detecting shadows in disks induced by infall

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ABSTRACT

Observations performed with high-resolution imaging techniques have revealed the existence of shadows in circumstellar disks that can be explained by the misalignment of an inner disk with respect to an outer one. The cause of misalignment, however, is still a matter of debate. In this study, we investigate the feasibility of observing shadows induced by one prominent scenario that may lead to misalignment, which involves the late infall of material onto a protostellar system. In particular, we used previously performed hydrodynamical simulations of such events and we generated flux maps in the visible, near-infrared, submillimeter, and millimeter wavelength ranges using Monte Carlo radiative transfer. Based on those results, we derived synthetic observations of these systems performed with the instruments SPHERE/VLT and ALMA, which we used as a basis for our subsequent analysis. We find that near-infrared observations with SPHERE are particularly well suited for detecting shadows via direct imaging alongside other features such as gaps, arcs, and streamers. On the contrary, performing a shadow detection based on reconstructed ALMA observations is very challenging due to the high sensitivity that is required for this task. Thus, in cases that allow for a detection, sophisticated analyses may be needed, for instance by the utilization of carefully constructed azimuthal profiles, aiding the search for potentially shallow shadows. Lastly, we conclude that a late infall-induced disk misalignment offers a plausible explanation for the emergence of shadows observed in various systems.

Key words. accretion, accretion disks – hydrodynamics – radiative transfer – protoplanetary disks – ISM: kinematics and dynamics

1. Introduction

Circumstellar disks are the birth locations of planets and they form as a byproduct of the star formation process. The ability to perform high-contrast and high-sensitivity observations of these disks with modern telescopes offers the opportunity to constrain their properties, particularly their spatial structures. Observations of scattered light, for instance, have revealed shadow features in various systems, including PDS 66 (Wolff et al. 2016), HD 142527 (Avenhaus et al. 2017), HD 100453 (Benisty et al. 2017), HD 169142 (Bertran et al. 2018), RXJ1604.3-2130 (Pinilla et al. 2018), HD 139614 (Muro-Arena et al. 2020), HD 34700 (Uyama et al. 2020), SU Aur (Ginski et al. 2021), and TW Hya (Debes et al. 2023). Moreover, shadows were detected for dust continuum observations of MWC 758 (Boehler et al. 2018) and for dust continuum and 12CO J = 2–1 line emission observations of RXJ1604.3-2130 (Stadler et al. 2023), as well as for observations of the 12CO J = 2–1 line of TW Hya (Teague et al. 2022). Recent studies have suggested that the presence of such features in scattered light observations of disks performed with the Spectro-Polarimetric High contrast imager for Exoplanets REsearch (SPHERE; Beuzit et al. 2019) at ~1 μm (H, R′, I′, J, and K bands) may be best explained by a configuration where an inner disk is misaligned with respect to an outer disk (Avenhaus et al. 2014; Marino et al. 2015; Benisty et al. 2017, 2018; Casassus et al. 2018; Ginski et al. 2021). In such a misaligned configuration, the illumination of selected parts of the outer disk by the central star is prevented by the inner disk. While there is a consensus that misalignment between inner and outer disk is a good explanation for the presence of the observed shadows, there is an ongoing debate about the origin of misalignment (see PPVII reviews Benisty et al. 2023; Pinte et al. 2023). Broadly speaking, we can distinguish among two main scenarios. The first scenario suggests that the primordial disk breaks apart and subsequently the inner and outer disk become misaligned to each other. The break-up and misalignment can be induced by a perturber such as an embedded massive planet, brown dwarf, or binary companion that may be located inside (Nixon et al. 2013; Owen & Lai 2017; Nealon et al. 2018; Zhu 2019) or outside the disk (Doğan et al. 2015). Also, a combination of an inner perturber, such as a planet, and an external perturber, such as a wide-orbit binary companion, is discussed to explain this phenomenon (Gonzalez et al. 2020; Nealon et al. 2020). In the other scenario, the outer disk forms from material with a different orientation of net angular momentum than the inner disk that has already formed earlier (Thies et al. 2011; Kuffmeier et al. 2021). This idea is in line with the possibility of infall onto protostellar systems that form in turbulent birth environments of giant molecular clouds, as seen in models (Padoan et al. 2014; Kuffmeier et al. 2017, 2023; Bate 2018) and as observed in star-disk systems that are associated with streamers (e.g., Le Gouët et al. 2019; Pineda et al. 2020; Valdivia-Mena et al. 2022, 2023, see also Pineda et al. 2023, for a recent review of star formation, including constraints from asymmetric infall via streamers). The present study is motivated by these predictions of infall in models, considering observations showing extended...
arm structures around presumably more evolved Class II young stellar objects such as AB Aur (Grady et al. 1999), SU Aur (Akiyama et al. 2019; Ginski et al. 2021), GM Aur, (Huang et al. 2021), Elias 2-27 (Paneque-Carreño et al. 2021), DR Tau (Mesa et al. 2022; Huang et al. 2023), RU Lup (Huang et al. 2020), and DO Tau (Huang et al. 2022), as well as strong indications of late infall from statistics of reflection nebulae (Gupta et al. 2023). Here, we explore a scenario that links the occurrence of late infall to the observation of shadows. We investigate the feasibility of detecting observable shadow features induced by misaligned disks that have formed as a result of late infall. For that purpose, we present and analyze maps of scattered and thermally emitted light from the dust phase that are based on snapshots of previously conducted hydrodynamical simulations of star-disk encounters with an infalling cloudlet (Kuffmeier et al. 2021). These maps have subsequently been post-processed to generate synthetic observations at different observing wavelengths. This allows us to test whether infall is a plausible explanation for the shadow features found in scattered light, thermal continuum emission, and line emission observations of real systems.

2. Methods

In the following, we describe the procedure we applied to generate synthetic observations, namely, the post-processing of results of radiative transfer simulations that are based on previously performed hydrodynamical simulations. The underlying hydrodynamical simulations were carried out with the moving-mesh code AREPO¹ (Springel 2010; Pakmor et al. 2016). The setup of the hydrodynamical simulations are presented in detail in a recent paper (Kuffmeier et al. 2021) and we only briefly summarize the main features of the underlying models. In the hydrodynamical runs, it was investigated how the gravitational potential of a star affects the dynamics of a cloudlet of gas that passes by the star. As a consequence of angular momentum conservation, such an encounter event leads to the formation of a new disk if the cloudlet has a non-zero impact parameter \( b \). The cloudlet was initialized at a given location:

\[
\mathbf{r}_{\text{init,cloudlet}} = \begin{pmatrix}
R_{\text{cloudlet}} \\
\xi_{\text{cloudlet}} \\
\eta_{\text{cloudlet}}
\end{pmatrix} = \begin{pmatrix}
-3.22 R_{\text{cloudlet}} \\
-b \cos \alpha \\
-b \sin \alpha
\end{pmatrix}
\]

where \( \alpha \) is the infall angle of the cloudlet measured with respect to the \( xy \)-plane of the coordinate system. The cloudlet radius \( R_{\text{cloudlet}} = 887 \) au and the impact parameter \( b = 1774 \) au correspond to 0.4 \( b_{\text{crit}} \) and 0.8 \( b_{\text{crit}} \), respectively. Here, \( b_{\text{crit}} \) describes the impact parameter at a test particle that encounters a 2.5 \( M_\odot \) star with velocity, \( v_i \), would be deflected by 90° (see Sect. 2 in Dullemond et al. 2019). The mass of the cloudlet was set to:

\[
M_{\text{cloudlet}}(R_{\text{cloudlet}}) = 0.01 M_\odot \left( \frac{R_{\text{cloudlet}}}{5000 \, \text{au}} \right)^{2.3}.
\]

It was initialized with a uniform density distribution, \( \rho_{\text{cloudlet}} \), and the density of the background gas was set to \( \rho_{bg} = \frac{\rho_{\text{cloudlet}}}{37} \). Furthermore, we enforced turbulent motions within the cloudlet (for more details see Kuffmeier et al. 2020, 2021). We assumed an isothermal temperature for the gas of 10 K. The cloudlet approaches the central star (modeled as a point source with mass \( M_\star = 2.5 M_\odot \)) with a velocity of

\[
\mathbf{v}_{\text{cloudlet}} = \begin{pmatrix}
v_\text{x,cloudlet} \\
v_\text{y,cloudlet} \\
v_\text{z,cloudlet}
\end{pmatrix} = \begin{pmatrix}
0 \\
0 \\
v_\parallel = 10^3 \, \text{cm} \, \text{s}^{-1}
\end{pmatrix},
\]

while the background gas is at rest with respect to the central star.

The star hosts a circumstellar disk with an initial density profile of \( \Sigma = \Sigma_0 \left( \frac{r}{a} \right)^{-p} \) between 20 au < \( r \) < 500 au. Inside and outside the disk, this profile was tapered off to the background density using a logistic function. In this paper, we focus on post-processing the previously performed runs with \( \Sigma_0 = 170 \, \text{g cm}^{-2} \) and \( p = 1.5 \). We considered infalling angles \( \alpha \) of 35°, 60°, and 90° (i.e., runs 3, 4, 5, 10, and 11 in Kuffmeier et al. 2021). For angles of 35° and 60° the inner disk was either set up with prograde (in runs 3 and 4, respectively) or retrograde rotation (in runs 10 and 11, respectively) with regard to the rotation of the newly forming outer disk. In this study, we mainly show and discuss results of the case of perpendicular infall (i.e., run 5 in Kuffmeier et al. 2021, column density plots are shown in Fig. B.6) with an inclination angle of the infalling cloudlet of \( \alpha = 90° \).

Radiative transfer post-processing

To simulate synthetic observations of scattered light and dust emission, we utilized the publicly available Monte Carlo (MC) radiative transfer (RT) code POLARIS² (see Reissl et al. 2016, 2019, 2020). POLARIS uses a Voronoi grid similar to the native grid of the AREPO code for performing RT simulations, hence, no re-gridding of the HD data is required. The dust was modeled assuming spherical grains of distinct radii, \( a_{\text{eff}} \), and with optical properties corresponding to a mixture of 37.5% graphite and 62.5% (astro)silicate (Draine & Lee 1984; Laor & Draine 1993; Draine 2003). The grain size distribution follows a power-law \( a_{\text{eff}}^{-2.5} \) typical for the ISM (for details, see e.g., Mathis et al. 1977; Li & Draine 2001). However, for the range of grain radii, we assumed a considerable grain growth within the disks leading to a range of \( a_{\text{eff}} \in [5 \, \text{nm}, 10 \, \mu\text{m}] \). For the spatial distribution of the dust we utilize a constant dust mass to gas mass ratio of 1%.

In a first post-processing step, we calculated the underlying dust temperature, assuming an equilibrium of absorbed and re-emitted radiation for each grain size. For the radiation field, we considered the spectral emission of the central star as well as an interstellar radiation field (ISRF) typical for our Galactic neighborhood (Mathis et al. 1983). In a second step, we performed monochromatic MC dust-scattering simulations as well as non-probabilistic RT simulations to generate thermal dust emission maps utilizing a ray-tracing algorithm, assuming either of three inclination angles of \( \iota \in \{0°, 45°, 90°\} \) and observing wavelengths of \( \lambda = 0.6263, 1.245, 2.182, 850, \) and 1300 μm.

3. Results and discussion

In the following, we assess the feasibility of detecting shadows cast onto the outer disk at different observing wavelengths based on synthetic scattering and dust emission maps. In Sect. 3.1, we show the results of simulated observations in the visible and near-infrared (VIS/NIR) wavelength range performed with

¹ https://arepo-code.org/
² https://portia.astrophysik.uni-kiel.de/polaris/
SPHERE, which provides a resolution that is high enough to regularly resolve small-scale structures in protoplanetary disks. In this wavelength range, the observed flux is dominated by stellar radiation that is scattered off the photospheres of the disks. In this case, shadows emerge due to blocked irradiation of the outer disk along the direction in which both disk mid-planes align, leading to a potentially observable contrast between the irradiated and shadowed sections of the outer disk. This effect is for the most part geometrical and the feasibility of a detection primarily depends on the flux level and emerging contrast.

Due to the reduction of heating irradiation, the shadowed regions cool down, resulting in a decrease in the observed flux in the submillimeter and millimeter (submm/mm) wavelength range and the formation of apparent shadows, which can also lead to observable arc-like features (see for instance Casassus et al. 2015). However, for their emergence, the shielded regions in the outer disk need to cool down sufficiently fast before the relative orientation of the disks changes and the shadowed region shifts. The cooling and heating timescales and their potential effects on observations are the topic of Sect. 3.2.

Lastly, in Sect. 3.3, we simulate observations performed with the Atacama Large Millimeter/submillimeter Array (ALMA; ALMA Partnership et al. 2015) in the submm/mm wavelength range. In this case, the inner and outer disks are almost optically thin and corresponding flux maps are for the most part determined by the spatial temperature and density distributions of both disks. A successful detection of the emerging shadows in this wavelength range therefore likewise depends on the observed contrast between the shadowed and the adjacent illuminated regions and the total flux of the system.

Since realistic detection limits for both instruments generally depend on various properties of the observed system, we used HL Tau (RA: 4h31min38s, Dec: +18°13’57”, J2000, Kwon et al. 2011) as a proxy, a system composed of a T Tauri star hosting a protoplanetary disk located in the close-by Taurus star-forming region at a distance of ~140 pc (Rebull et al. 2004). Its spectral type is K5 (White & Hillenbrand 2004) and its flux values in the J and V bands are 10.624 mag (Cutri et al. 2003) and 14.49 mag (Zacharias et al. 2012), respectively. In the context of this study, using HL Tau as a proxy rather than a more evolved, brighter star yields comparably low, and thus conservative, detectable contrast value estimates. Moreover, it is worth mentioning that we assumed different distances to the reference star throughout this paper, which may differ from the actual distance to HL Tau. In particular, we assumed a generic value of \( d = 140 \) pc, roughly corresponding to the distance to the Taurus star-forming region, which allows us to compare our results to observations of the SU Aur system. Additionally, we investigated the feasibility of detecting shadows in more distant systems and assumed, for that purpose, a distance of 400 pc.

### 3.1. SPHERE observations

To assess the feasibility of detecting shadows in the outer disk, we generate synthetic observations for the instruments IRDIS and ZIMPOL. Both instruments are installed on SPHERE at the telescope UT3 of the VLT with a diameter of \( D = 8.2 \) m. Furthermore, we assume the usage of broadband filters and coronagraphs to enable high-contrast observations. For the instrument ZIMPOL in the VIS wavelength range, we simulate observations performed in the mode ZIMPOL_I using the broad band filter R_PRIM with a central wavelength of \( \lambda = 0.6263 \) μm and the recommended classical Lyot coronagraph V_CLC_M_WF with an inner working angle (IWA) of 0.155 mas. For the simulated IRDIS observations in the NIR wavelength range, we assume the usage of the classical imaging mode, either using the broad band filter BB_J with a central wavelength of \( \lambda = 1.245 \) μm or the broad band filter BB_Ks with a central wavelength of \( \lambda = 2.182 \) μm. For these synthetic observations, we furthermore assume the utilization of the apodized Lyot coronagraphs N_ALC_YJH_S (IWA = 0.15 mas) or N_ALC_Ks (IWA = 0.2 mas), respectively. For illustration, Fig. 1 shows an ideal flux map of a simulated system for an observing wavelength of 1.245 μm in the top plot.

On the basis of simulated ideal polarimetric observations of the Stokes parameters, \( Q \) and \( U \), we went on to create maps of the azimuthal Stokes parameters (de Boer et al. 2020),

\[
Q_0 = -Q \cos 2\phi - U \sin 2\phi, \tag{4}
\]
\[
U_\phi = +Q \sin 2\phi - U \cos 2\phi,
\]
where \( \phi \) describes the azimuthal coordinate, which for any cartesian pixel at position \((x, y)\) is given by
\[
\phi = \arctan \left( \frac{x - x_*}{y - y_*} \right),
\]
with \((x_*, y_*)\) as the position of the star. In comparison to Eq. (6), de Boer et al. (2020) used an additional offset angle, \( \phi_o \), which is not required in our simulations. This quantity was introduced to account for the rotation of the derotator, which was used over the course of multiple observational cycles, which otherwise would have led to a likewise rotation of apparent polarization vectors. Exemplarily, results for an ideal \( Q_\nu \) map are shown in the middle plot of Fig. 1. For comparison purposes, the bottom plot shows the results of observations of the SU Aur system, which were performed with SPHERE/IRDIS in the \( H \) band (Ginski et al. 2021). Each of these plots shows, alongside extended arm features, namely, streamers, two strikingly dark regions extending from their respective centers outward in almost diametrically opposed directions. In order to assess the feasibility of observing such shadows, synthetic observations are constructed on the basis of these ideal flux maps.

A synthetic observation at a given observing wavelength is generated by convolving the corresponding ideal flux map with a Gaussian beam, using a wavelength-dependent full width at half maximum (FWHM) of \( 1.22 \lambda / D \). Other instrument specific properties that may affect the observation have been neglected for this analysis. Subsequently, for the simulated flux of each pixel \((f_{\text{sim}})\) the corresponding contrast \( C_\text{max} = -2.5 \log_{10}[f_{\text{sim}}/f_{\text{max}}] \) was calculated, where \( f_{\text{max}} \) is the maximum pixel value in each map, located at the projected position of the star on the map. Lastly, the central region was masked according to the size of the IWA.

The feasibility of SPHERE to detect faint sources is limited by the contrast between its detected flux and the flux of the star. The detection limit additionally depends on the specifics of the instrument, in particular, the filter and coronagraph, and the distance between the source and the star. In order to estimate realistic detection limits, we made use of the SPHERE ESO exposure time calculator (ETC)\(^4\). We thereby obtained \( 5\sigma \) performance curves which provide the maximum contrast values, namely, the detection limits that allow for a detection as functions of the distance to the star. If the contrast between the source and the star exceeds this limit, it is too dim and can thus not be detected. Since these limits generally depend on the celestial coordinates of the observed system as well as on its specific properties, we use properties of the reference star to obtain generic estimates. Furthermore, we assume that the observations are performed using the pupil-stabilized mode, each with an exposure time of 3600 s as well as a DIT of 8 s for IRDIS or 10 s for ZIMPOL. A list of selected contrast detection limits for the considered three wavelengths is presented in Table 1. We note, that particularly for faint disks readout noise can play a critical role, resulting in a need for higher DIT values. We confirmed in a test, though, that the effect of its increase to 64 s (50 s) for IRDIS (ZIMOL) had no substantial impact on the qualitative validity of our results. To further ensure the quality of our results, we conducted an additional test to confirm that even a 5 mag artificial increase of the brightness of the star also did not qualitatively affect our results.

\(^4\) https://www.eso.org/observing/etc/
the comparison of observations at different wavelength, the displayed synthetic observations in the VIS/NIR and submm/mm wavelength ranges in this figure were all generated assuming the same distance of \( d = 140 \) pc. Interestingly, the synthetic observations with IRDIS at 1.245 \( \mu \)m often lead to more pronounced features than comparable observations at 2.182 \( \mu \)m, which can be attributed to the better contrast detection limits provided by SPHERE in the \( J \) band. Therefore, we conclude that scattered light observations, particularly in the NIR, allow us to directly image these shadows when using SPHERE. Next, we analyze the feasibility of observing shadows in the submm/mm wavelength range using ALMA.

### 3.2. Dust cooling and heating

As shown in the ideal flux map in Fig. 1, direct stellar radiation cannot illuminate the entire outer disk evenly because of the shadowing effects caused by the inner disk. Consequently, these shadowed regions are heated indirectly only by scattered light and re-emitted radiation from the illuminated regions of the outer disk, leading to a reduced dust temperature compared to the primarily directly heated regions of the outer disk\(^5\).

In the following, we aim to investigate whether the resulting discontinuity in the spatial temperature distribution can be detected with ALMA. However, our synthetic RT observations represent merely a snapshot and cannot account for the dynamical processes of hot dust material entering the shadowed regions. Thus, before validating the feasibility of such a shadow detection, we have to evaluate the potential impact of dynamic processes on the dust temperature in the shadowed regions. If for instance the dust cooling is inefficient, the hot material may not reach a lower temperature within the transit time of the shadow for the effect to become detectable. The defining factor is the cooling time of dust grains itself.

A similar model was explored in Casassus et al. (2019). However, in their model, a dust-gas interaction was assumed in order to determine the temporal evolution of the dust temperature within the shadowed region. In contrast to Casassus et al. (2019), we assume that the dust is sufficiently far away from the central star. Hence, the heating and cooling processes are dominated by radiation and not by gas-dust interactions such as viscous heating. Such conditions can be expected to prevail in the outer disk.

As a result, the temporal evolution of the dust temperature, \( T_d \), simply follows:

\[
\frac{dT_d}{dt} = \kappa_{abs}(T_d) \left( T_{RT} - T_d^4 \right),
\]

where

\[
\kappa_{abs}(T_d) = \frac{\pi}{\sigma T_d^4} \int \kappa_{abs}(T_d) d\lambda
\]

is the Planck mean opacity, \( \sigma \) the Stefan–Boltzmann constant, and \( T_d \) the dust temperature in the non-shadowed outer disk calculated with the MC approach. The opacity of absorption, \( \kappa_{abs}(T_d) \), corresponds to that of the optical properties of the dust model outlined in Sect. 2.1. For the heat capacity \( C_v(T_d) \) of the grain material, we use the spline interpolated values of the data presented in Draine & Li (2001).

In Fig. 3, we show the resulting dust cooling process for three exemplary distances, \( R \), from the central star assuming a Keplerian rotation of the outer disk and a typical opening angle of 15° for the shadowed region (see upper plot in Fig. 1). At that distance, the MCRT calculations predict a temperature decline from ≈100 K in the fully illuminated outer disk down to ≈40 K in the shadowed regions. Under such conditions, grains with sizes \( a_{eff} \leq 125 \) nm can efficiently cool down to the lowest temperatures before reaching the end of the transit period. Only the largest but least abundant grains with sizes of \( a_{eff} \geq 300 \) nm...
cannot fully cool down to the lowest temperature. For the following analysis, we therefore make the assumption that the transit time does suffice for efficient cooling to take place inside the shadowed regions. Hence, we approximate the underlying temperature distributions of our models with the equilibrium temperature distributions calculated using MCRT simulations.

### 3.3. ALMA observations

The ideal flux maps of all considered configurations were processed with the Common Astronomy Software Applications (CASA) tool, version 6.4.1 (McMullin et al. 2007). We generated synthetic ALMA observations for \( \lambda = 850 \mu m \) (band 7) and 1300 \( \mu m \) (band 6), assuming the celestial coordinates of the reference star as well as a distance of 140 pc. These synthetic observations were performed for configurations C43-4, C43-5, C43-6, and C43-7 using the simobserve task of CASA, assuming a rather long total observation time of \( \Delta_{\text{obs}} = 12 \) h to obtain high quality results. We note that such a long observation time cannot be acquired with ALMA during a single night for the considered reference star, however, as will be shown in the following, the feasibility of a shadow detection is limited by the sensitivity, which can be achieved by performing multiple observations. The combination of these bands and configurations results in angular resolutions ranging from about \( \theta_{\text{res}} = 0.064-0.4\) arcsec\(^6\), which is comparable to the width of the shadow features found in our ideal flux maps at different radial distances from the star. Subsequently, the tclean task of CASA was performed to reconstruct a sky model, using the spectral mode mfs and natural weighting, in order to achieve the maximum imaging sensitivity. The threshold was set to the values that were determined with the ALMA Sensitivity Calculator\(^7\). We find that due to the high level of noise, it is generally difficult to infer the presence of a shadow simply by visually inspecting these synthetic observations. While the sensitivity of ALMA does suffice to detect the inner disk in all of the considered cases, only a fraction of the simulated maps show features that originate from further extended structures. The features may include an outer disk that is separated from an inner disk through a gap, arc-like structures that are often close to the inner rim of the outer disk, spiral arms, and (albeit rarely) even a low contrast shadow in the region of the outer disk. We note in passing that supplementary tests have been performed, where the considered maximum grain size of dust grains in the inner disk has been artificially increased to 32 \( \mu m \), assuming the celestial coordinates of \( \mu = 850 \mu m \) (band 7) = 0.064–0.4 arcsec\(^6\), which is comparable to the width of the shadow features found in our ideal flux maps at different radial distances from the star. Notably, this change did not appear to have a significant qualitative impact on the simulation outcomes. As a result, it will not be taken into consideration in the subsequent analysis.

An analysis of our results suggests that for the shadows to be detectable, the system has to be misaligned and formed with an infall angle of \( \alpha \neq 0 \). Otherwise, a detection with ALMA seems unfeasible for all investigated systems. Moreover, we find that the best combination of considered observing wavelength and configuration depends primarily on the size of the reconstructed beam, namely, it requires a trade-off between sensitivity and resolution. In our case, this corresponds to a combination of the shorter wavelength with a compact ALMA configuration or the longer wavelength with a wider configuration. Figure 4 exemplarily shows a reconstructed synthetic ALMA observation using configuration C43-4 (rms=\(3.32 \times 10^{-4} \) Jy beam\(^{-1}\)) based on run 5 at 150 kyr assuming a distance of 140 pc (top). The beam (gray) is displayed in the lower right corner of the plot. Corresponding ideal flux map (bottom).

#### 3.3.1. Instrument sensitivity

The fact that most of these shadow features can clearly be seen in ideal flux maps, but are not visible in corresponding synthetic simulations, can be explained by an overly small ratio of the flux emitted by the outer disk to the sensitivity provided by ALMA.

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\(^7\) [https://almascience.eso.org/proposing/sensitivity-calculator](https://almascience.eso.org/proposing/sensitivity-calculator)
To verify this, we assessed the feasibility of detecting the shadows for the system shown in Fig. 4 with future instrumentation that offers an improved sensitivity. This was done by artificially increasing the values of the corresponding ideal flux map pixel-wise by a factor of 10 before post-processing it with CASA. The results of this analysis for configurations C43-5 (upper row), C43-6 (middle row), and C43-7 (bottom row) can be found in Fig. B.5, where the left column depicts the results corresponding to the original unaltered ideal flux map and the right column the results after the artificial increase of flux values. We find that this increase in flux, which is equivalent to a likewise improvement of instrument sensitivity, is already sufficient for the emergence of shadow features in observations using any of the four considered configurations. Additionally, it is worth mentioning that at a distance of 140 pc, only configuration C43-4 provides a maximum recoverable scale (MRS) for both wavelengths that is large enough to encompass the inner disk and a part of the outer disk; however, this is not the case for any of the other considered much wider configurations. Nevertheless, since the change in orientation of the disks and, consequently, the position of the shadow is negligible on timescales of a few years or decades (Figs. 12 and 13 in Kuffmeier et al. 2021, show that the change in orientation is less than 1° on timescales of a few thousand years), it is possible to combine observations in the more extended configurations with observations in the compact configurations to obtain a better UV coverage. Figure B.4 exemplarily shows the results of a multi-configuration observation, combining interferometric data of a high-resolution observation using configurations C43-7 (1 × ΔRobs) with data obtained for configuration C43-4 (0.23 × ΔRobs), which covers a sufficiently large angular scale to encompass the whole system. As a result, the addition of configuration C43-4 data improves the synthetic observation, allowing for a visual detection of a weak shadow feature in the lower left quadrant of the image.

3.3.2. More distant systems

We investigated the feasibility of detecting these shadows for more distant systems using configuration C43-4. Figure 5 shows such a synthetic observation of the same system as investigated before (see Fig. 4), but now at an increased distance of 400 pc. At this distance, the shadow feature is significantly narrower in the ideal flux map and, thus, appears notably smeared out in the synthetic observation, leading to a much smaller observed flux reduction in the region of the shadow. As a result, it can barely be seen in Fig. 5, even after clipping the color bar. This is the case for the top-right quadrant in particular, where it seems to have completely vanished. Hence, we conclude that although the likelihood of detecting shadows in systems at greater distances appears reduced, the potential for the spatial extension of these shadows, possibly spanning hundreds or even thousands of astronomical units, still allows for feasible detections.

3.3.3. Detection tool: Azimuthal profiles

Due to the high level of noise present in the reconstructed ALMA observations (see e.g., Fig. 5) and the generally low flux level in the shadowed region, it is often difficult to infer the presence of the shadow solely based on a visual inspection of the observation. However, while the flux value in the synthetic observation may (due to underlying noise) strongly deviate from its value in the ideal flux map, the process of integrating over a region in the map can effectively mitigate this issue, resulting in a smaller relative deviation. Since the shadow is cast onto the outer disk, extending out approximately in radial direction from the inner edge of the disk to its far-out regions, it leaves a characteristic feature in the form of two almost diametrically opposed dips in the azimuthal brightness profile. Here, an azimuthal profile is computed by radially integrating the flux map along different azimuthal directions, \( \phi \in [0, 2\pi] \), in the plane of the sky, starting from the center of the map.

To calculate the azimuthal profile, we used CartToPolarDetector\(^8\) (Krieger & Wolf 2022), a tool that precisely converts a Cartesian detector to its polar representation. For the obtained polar flux maps, we used 360 × 720 polar pixels (in azimuthal × radial directions) and a detector radius that corresponds to the specific MRS of the underlying configuration and wavelength of the map. Since the inner disk is significantly brighter than the outer disk, a central region of the flux map was masked. Furthermore, to avoid integrating noise-dominated regions in the map, it was necessary to limit the radial extent (\( \Delta r \)) of the integrated region.

Figure 5 shows the azimuthal profiles obtained from the corresponding ideal flux map (blue) and the synthetic observation (red). For the latter, we limited the integrated region to a radial range of \( \Delta r = 300 \) au. Furthermore, we assumed an inner disk size and shape (hatched central region) that approximates the inner disk (as seen in the ideal flux map) and masked the inner region (inside the gray dashed line) according to one FWHM of the synthetic ALMA beam. A detailed description of our method to calculate these azimuthal profiles is presented in Sect. A of the appendix.

For every direction \( \phi \), the distance of the displayed azimuthal profile to the center of the map is proportional to the functional value of the azimuthal profile in that specific direction. We note, that the depiction of these profiles in polar coordinates in combination with the synthetic observation in the

\[ \text{https://github.com/anton-krieger/CartToPolarDetector} \]
We investigated the feasibility of detecting shadows in observations of circumstellar disks around young stellar objects, that form as a consequence of a late infall event. It is based on snapshots of previously performed hydrodynamical simulations of a star hosting a circumstellar disk that collides with a cloudlet (Kuffmeier et al. 2021). These simulations were subsequently post-processed using MC radiative transfer simulations to calculate wavelength-dependent ideal flux maps in the NIR/VIS and the submm/mm wavelength range (see Sect. 2.1), which exhibit clear shadow features that extend across the outer disk. To assess the feasibility of detecting such shadows with real observations, synthetic observations were generated from these maps, assuming the usage of the instruments SPHERE/VLT and ALMA for the VIS/NIR and submm/mm wavelength range, respectively.

In short, this involved convolving the ideal maps with a beam of wavelength-dependent size in the case of SPHERE observations (see Sect. 3.1) as well as the simulation of an observation and subsequent image reconstruction using CASA in the case of ALMA (see Sect. 3.3). The obtained synthetic observations in this way have served as a starting point from which the following conclusions were drawn. Figure B.2 shows synthetic observations exemplarily for all considered observing wavelengths of SPHERE and ALMA, assuming a distance of $d = 140$ pc to allow for a direct comparison of observations at different wavelengths. We find that shadow features can be observed both via scattered light observations with SPHERE and via thermal emission maps with ALMA. First, we recall the key points of our analysis of our derived synthetic SPHERE observations below:

- We apply realistic contrast detection limits obtained from the ETC and assumed a distance of $140$ pc to the simulated system. The corresponding synthetic observations exhibit various features like gaps, arcs, streamers, and pronounced shadows;
- We find the contrast between the shadowed region in the outer disk and neighboring regions to be well inside the detectable range for systems with various relative orientations between the inner and outer disk observed at different inclination angles;
- Observations in the NIR wavelength range are generally well suited for a detection of shadows. Our analysis suggests that observations in the $J$ band with the instrument IRDIS at $1.245 \mu m$ can be expected to yield the most promising results. On the contrary, a detection in the VIS wavelength range seems to be hindered due to a relatively high stellar flux.

Next, we recall the key points of our analysis of the obtained synthetic ALMA observations:

- We estimate that for grains of sizes $a_{\text{eff}} \leq 250 \text{ nm}$, which likely represent the majority of all available grains in the shadowed region of the outer disk, the shadowing time does suffice for efficient cooling (see Sect. 3.2.1).
- Maps were reconstructed for simulated observations in two bands ($6$ and $7$) and four configurations (C43-4 to C43-7), assuming a distance of $140$ pc to the systems;
- Reconstructed maps exhibited various features, including gaps, arcs, streamers, and (rarely) low contrast shadows;
- Our results suggest that detecting a shadow is a challenging task as the flux of the outer disk is rather low compared to the provided sensitivity of the instrument, which leads to noisy reconstructed maps. The most promising results were obtained using a combination of band 7 ($850 \mu m$) and the rather compact configuration C43-4. In rare cases that do allow for a shadow detection, a careful inspection of the map is mandatory due to the high level of brightness of the inner disk;
- We find that for the impact of the shadows to be detectable, the system has to be misaligned and formed with an infall angle of $\alpha \neq 0$. Furthermore, if the system has not yet evolved for a sufficient amount of time ($\leq 50 \text{ kyr}$), a detection is rather unlikely;
- Detecting shadows in systems at a (greater) distance of $400$ pc may be more challenging, but still be possible for certain systems (see Sect. 3.3.2). Therefore, we investigated the possibility of retrieving the information of the presence of a shadow with these reconstructed maps based on azimuthal profiles. We find that these profiles can aid the search for very shallow shadow features that may be overlooked by just visually inspecting the observations.

We conclude that an event of late infall of material onto the system of a star hosting a disk has the potential to cause shadow features that are observable with currently available instruments. In particular, this is the case with high-contrast and high-sensitivity instruments such as SPHERE and ALMA in the VIS/NIR and submm/mm wavelength range, respectively. Hence, the scenario of late infall does offer a plausible explanation for the emergence of shadows that are observed in real systems.

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References

Pineda, J. E., Segura-Cox, D., Caselli, P., et al. 2020, Nat. Astron., 4, 1158
Appendix A: Azimuthal profile determination

Fig. A.1. Ideal flux map at 850 μm based on run 5 at 150 kyr. The blue curve shows the corresponding azimuthal profile, which was obtained after masking the central circular white region.

In the following, we present a method to determine and to analyze azimuthal profiles in order to detect radially extending shadow features in observations. All analyses presented in this section are based on run 5 at 150 kyr assuming a distance of 400 pc. Figure A.1 shows the corresponding ideal flux map for this system at 850 μm, overlayed with its ideal azimuthal profile (blue curve).

The shape of the masked central region (white region) is circular and chosen such that it encompasses the whole inner disk. For every direction $\phi$, the displayed distance of the azimuthal profile to the origin of the polar grid is proportional to the functional value of the azimuthal profile in that specific direction. For all our models, we find that the locations of both shadow features in the flux map clearly match the positions of dips in the ideal azimuthal profile.

Appendix A.1: Masking methods

In the case of the synthetic ALMA observations, on the contrary, a more sophisticated masking method has to be used to calculate an azimuthal profile that exhibits dips matching both locations of the shadow, without introducing additional features that may lead to a false or no shadow detection. In general, there are several factors that make the calculation of an azimuthal profile which serves this purpose difficult: the low flux level of the outer disk, a small flux difference between the regions inside and the regions just outside the shadow, the shape of the synthesized beam, the inclination of both the inner and the outer disk, and the fact that the FWHM of the beam and the inner disk are of similar angular extent.

Therefore, we tested different post-processing methods for retrieving the information of the presence of shadows from the synthetic ALMA observations. In the end, however, none of them were able to unambiguously lead to a detection, which is for the most part a consequence of the generally low flux level of the outer disk. Nonetheless, we were able to make a comparison and we identified the method that resulted in the best azimuthal profiles for detecting shadows in disks and can be used as a tool to find shallow shadow features.

Before describing the method in Sect. A.2, it is worth mentioning the various other approaches that generally lead to unwanted features in the azimuthal profile, making its appearance differ strongly from their ideal counterpart. An inapt approach would often either lead to a lack of dip features in the azimuthal profile or to a high abundance of them with no clear pattern. For instance, we find that it does not suffice to mask a circular region, as this neither takes into account the specific shape and size of the inner disk, nor those of the beam. When masking a region that has the same shape as the synthesized beam instead (i.e., of its main lobe) and testing different total angular extents of the masked region, the azimuthal profile still exhibits undesirable features. This is most likely due to the fact, that in our models the inner disk has a size that is comparable to that of the beam, which leads to a spreading of its flux that does not match the shape of the beam alone. In another method that we tested, a certain number of the brightest pixels in the centers of the flux maps were removed. However, even when restricting the successive removal of the brightest pixels to those that are neighbors of previously removed bright pixels, this method leads to masked regions with very complex structures and various features in the azimuthal profile. This is partly due to the noise and partly due to the fact that the flux of the inner disk is spread according to the PSF such that it overlaps with the flux of the inner edge of the outer disk. Due to the former effect, there are additional undesirable features in the azimuthal profile. Given the latter, it can be expected that the dips, which indeed are a consequence of the shadows, become shallower and wider, thus decreasing the likelihood for a shadow detection.

Appendix A.2: Shadow retrieval

To generate the most suitable azimuthal profiles for detecting shadows in disks, we made use of the fact that the shape of the inner disk strongly resembles an ellipse, as can exemplarily be seen in Fig. 2. The method can then be summarized as follows: First, we make guesses regarding the shape and size of the inner disk by approximating it by an ellipse and calculate a beam-size and beam-shape dependent masking region that encompasses the guessed inner disk. Second, for different areas of the masked regions, we determine the best guessed disk sizes and shapes. Third, for these cases, we compute normalized azimuthal profiles, that result in the most reliable shadow predictions.

In particular, we tested different guesses for the inner disk by successively increasing its area, varying its eccentricity, and changing the orientation of its major axis. For any given inner disk guess, the masked area is calculated by extending the region of the guessed inner disk by at least the FWHM of the main lobe of the beam, that is, we calculate the area that is covered by the beam, when moving it along the outer edge of the guessed inner disk. By doing so, the masked area is adjusted according to the shape and size of both the inner disk and the beam. We note that if the noise level is not too high, it can be beneficial to use a value that is two to four times the FWHM instead, as this further reduces the impact of the inner disk on the determined azimuthal profiles. For each tested guessed inner disk, we then determine the area of the masked region $A_{\text{mask}}$, the flux of a one polar pixel wide rim region that surrounds the masked region $I_{\text{rim}}$, as well
as the total area of this rim region $A_{\text{rim}}$. As a result, each tested guessed inner disk corresponds to a point in the $A_{\text{mask}}$-$I_{\text{rim}}$ plane, with $I_{\text{rim}} = I_{\text{rim}}/A_{\text{rim}}$, as can be seen in Fig. A.2, where each black dot represents a different inner disk guess. Next, we defined the most suitable inner disk guesses as those, which minimize $I_{\text{rim}}$ for any given value of $A_{\text{mask}}$ (blue curve in Fig. A.2).

It is worth mentioning, that maximizing the flux of the masked area for a fixed guessed inner disk area does not work for our purpose, since this approach tends to favor unrealistically high eccentricities close to unity for the guessed inner disks. This behavior can be explained by the fact, that the masked area strongly increases with the eccentricity of the disk, such that these highly eccentric disks result in extremely stretched masked regions with very high $A_{\text{mask}}$ values.

Furthermore, we determined the approximate parameters of an ellipse that resembles the shape and size of the actual inner disk based on its ideal flux map (see bottom plot in Fig. 4) and computed the position of the corresponding point in the $A_{\text{mask}}$-$I_{\text{rim}}$ plane, which is shown as a red cross in Fig. A.2. Based on that we verified, that the approximate ideal disk shape and size indeed corresponds to a point in the $A_{\text{mask}}$-$I_{\text{rim}}$ plane that lies on the curve of most suitable inner disk guesses, for all considered models, configurations, and wavelengths.

Next, we compared different possible azimuthal profiles. Simply integrating the flux over a narrow azimuthal range in radial direction (as done for the ideal azimuthal profiles) did not suffice as it leads to a great abundance of minima in the profile. This occurs due to the fact, that the integration is performed over a region that is for the most part dominated by noise. We find that the quality of the azimuthal profile improves when restricting the radius, up to which the integration is performed. In particular, the best results were obtained when restricting the radial integration range to a constant length $\Delta r$, namely, depending on the direction $\phi$, the integration was performed starting from the outer edge of the masked region up to a distance of $\Delta r$. However, since the corresponding integrated area $A_{\phi}$ hence depends on the shape of the masked region, it is furthermore required to normalize the azimuthal profile for every direction according to $A_{\phi}$. Based on a comparison of different values of $\Delta r$ for various models, configurations, and wavelengths (compare with Fig. A.3), we find that for our synthetic observations $\Delta r = 300$ au often leads to the most reliable results and the most suitable azimuthal profiles for detecting shadows in disks. We note, that the best value for $\Delta r$ strongly depends on the quality of the observation and needs to be determined for each observation individually.

Figure A.3 exemplarily shows the resulting normalized azimuthal profiles for different values of $\Delta r$ ranging from 100 to 500 au (red curves). These plots suggest that in the considered range, higher values of $\Delta r$ lead to deeper dips in the azimuthal profile at the cost of a greater number of dips, i.e., the structure of the azimuthal profile becomes more complex. On the contrary, low values of $\Delta r$ typically lead to more shallow dips and a much smoother shape of the azimuthal profile. In the case of $\Delta r = 300$ au, for instance, two almost diametrically opposed dips can be seen, that hint at the presence of an underlying shadow, while other regions in the azimuthal profile are for the most part smoother. We also find, that these two dips appear at a similar position as the dips that are present in the ideal map. However, there are also different other minima present in the azimuthal profile, for instance in the direction $\phi \approx 135^{\circ}$, which are not present in the ideal azimuthal profile (blue curve). We note that in a similar analysis of synthetic ALMA observations of the same system at 1300 $\mu$m (band 6), we altogether found very similar trends, however, the shadow feature appears to be even more spread out due to the increased beam size. The corresponding azimuthal profiles are shown in Fig. A.4. Although the existence of two almost diametrically opposed dips in the azimuthal profile gives a strong indication for the presence of a shadow, false detections cannot be fully ruled out using this method alone. Moreover, it is generally difficult to decide which of the most suitable inner disk guesses is leading to the best azimuthal profile, unless the approximate shape of the inner disk is already known due to observations performed for instance in the VIS/NIR wavelength range (see Fig. 2). Generally, we find that the most suitable inner disk guesses with small values of $A_{\text{mask}}$ lead to azimuthal profiles that are comparably smooth, while those with high $A_{\text{mask}}$ values lead to azimuthal profiles with rather complex structures. Overall, this indicates that the most reliable strategy for detecting shadows in disks requires an analysis of these most suitable inner disk guesses and their corresponding azimuthal profiles and a search for a common shadow feature across those profiles, which would appear in the form of diametrically opposed dips. However, in the case of a high level of noise in the synthetic ALMA observations, as it is present in our simulations, it appears to be rather difficult to perform an unambiguous detection of shadows. Additionally, the size of the beam may often exceed the width of the shadow in the regions close to the inner edge of the outer disk, leading to a reduction of the contrast in brightness between the shadow feature and neighboring regions. Overall, applying the described method to real observations may provide evidence for the existence of shadows and justify an in-depth investigation of such a system regarding the possibility of a late infall event.

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Fig. A.2. Distribution of obtained data points corresponding to different guessed inner disk shapes and sizes (black dots) in the $A_{\text{mask}}$-$I_{\text{rim}}$ plane based on a synthetic ALMA observation of run 5 at 150 kyr and 850 $\mu$m. The blue curve marks the position of most suitable inner disk guesses. A red star highlights the position corresponding to an inner disk of approximately the shape and size of the (actual) inner disk as seen in the ideal flux map.

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Fig. A.3. Comparison of normalized azimuthal profiles (red curves) for five different radial integration distances $\Delta r$ based on run 5 at 150 kyr (corresponding to the synthetic ALMA observation shown in Fig. 5). The dashed red ellipse in the center of each plot shows the underlying assumed inner disk, whose properties were chosen according to those of the approximate ideal inner disk. The blue curves show ideal azimuthal profiles. Each red curve corresponds to the obtained normalized azimuthal profile of each plot, assuming the $\Delta r$ value above the plot.

Fig. A.4. Similar to Fig. A.3, now for a synthetic band 6 ALMA observation of the same system at 1300 $\mu$m.

Appendix B: Supplementary material

Appendix B.1: Azimuthal profiles

Figure B.1 shows normalized azimuthal profiles for an ALMA observation at 850 $\mu$m. For details, see Sect. B.1.

Figure B.1 shows normalized azimuthal profiles for the ideal (red) and the synthetic (blue) ALMA observation at 850 $\mu$m using configuration C43-4 based on the simulation of run 5 at 150 kyr assuming a distance of 400 pc. These profiles correspond to the profiles shown in Fig. 5. For details, see Sect. 3.3.2.

Appendix B.2: Synthetic observations

Figure B.2 shows synthetic SPHERE observations (left column) and synthetic ALMA observations (right column) for different bands. In particular, the synthetic ALMA observations are based on run 5 at 150 kyr and assume the usage of configuration C43-4 (upper right plot: rms=$3.32 \times 10^{-4}$ Jy/Beam); middle right plot: rms=$1.66 \times 10^{-4}$ Jy/Beam). Synthetic SPHERE observations are shown in the form of derived contrast maps based on the same run. For illustrative purposes, the hatched area of radius 400 mas in the centers of these plots is masked, and the color bar has been limited to the maximum range of detectable contrast values outside the masked region. Moreover, a distance of 140 pc is assumed for all five synthetic observations and the corresponding observing wavelength is displayed in the top right corner of each plot.
Fig. B.2. Collection of different synthetic SPHERE (left column) and ALMA observations (right column). For details, see Sect. B.2.
Appendix B.3: Time evolution

Fig. B.3. Synthetic ALMA observations at 850 \( \mu m \). For details, see Sect. B.3.

Figure B.3 shows synthetic ALMA observations at 850 \( \mu m \) using configuration C43-4 based on three different snapshots of run 5 assuming a distance of 140 pc: at 50 kyr (upper plot; rms=3.76 \times 10^{-4} Jy/Beam), 100 kyr (middle plot; rms=3.47 \times 10^{-4} Jy/Beam), and 150 kyr (lower plot; rms=3.32 \times 10^{-4} Jy/Beam).

Appendix B.4: Multi-configuration observations

Fig. B.4. Synthetic ALMA observations at 850 \( \mu m \). For details, see Sect. B.4.

Figure B.4 shows a synthetic ALMA observation at 850 \( \mu m \) using a combination of observations with configuration C43-7 and C43-4 (rms=4.04 \times 10^{-5} Jy/Beam) based on run 5 at 150 kyr assuming a distance of 140 pc. The corresponding beam (gray) is displayed in the lower right corner of the plot.

Appendix B.5: Instrument sensitivity

Fig. B.5 shows synthetic ALMA observations at 850 \( \mu m \) using configurations C43-5 (upper row; left plot: rms=1.62 \times 10^{-4} Jy/Beam; right plot: rms=1.62 \times 10^{-3} Jy/Beam), C43-6 (middle row; left plot: rms=6.60 \times 10^{-5} Jy/Beam; right plot: rms=6.61 \times 10^{-4} Jy/Beam), and C43-7 (bottom row; left plot: rms=3.09 \times 10^{-5} Jy/Beam; right plot: rms=3.07 \times 10^{-4} Jy/Beam) based on run 5 at 150 kyr assuming a distance of 140 pc. The left column shows results based on the unaltered ideal flux map, while the right column corresponds to the same ideal map with tenfold increased flux values. The corresponding beam (gray) is displayed in the lower right corner of each plot. For details, see Sect. 3.3.1.

9 See ALMA technical handbook, Table 7.5: https://almascience.eso.org/documents-and-tools/cycle9/alma-technical-handbook

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Fig. B.5. Synthetic ALMA observations at 850 µm. For details, see Sect. B.5.
Appendix B.6: Column density

Fig. B.6. Corresponding column density of three snapshots of run 5 at 50 kyr (upper plot), 100 kyr (middle plot), and 150 kyr (lower plot).

Appendix B.7: Temperature distribution

Fig. B.7. Temperature distributions corresponding to vertical cuts through the mid-plane of the outer disk. For details, see Sect. B.7.

Figure B.7 shows an averaged temperature distribution, which is based on run 5 at 150 kyr, corresponding to a vertical cut through the mid-plane of the outer disk which is either shadowed due to the inner disk (upper plot) or directly illuminated by the central star (lower plot). In particular, these results were obtained by averaging temperature distributions across an azimuthal range of $\Delta \phi = 0.1\pi$. 