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The innermost circumstellar environment of massive young stellar objects revealed by infrared interferometry

Thomas Preibisch, Stefan Kraus, & Keiichi Ohnaka

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

Abstract. We study the geometry of the inner (AU-scale) circumstellar region around the Herbig Be star MWC 147 with infrared long-baseline interferometry. By combining for the first time near- and mid-infrared spectro-interferometry on a Herbig star, our VLTI/AMBER and VLTI/MIDI data constrain not only the geometry of the brightness distribution, but also the radial temperature distribution in the disk. The emission from MWC 147 is clearly resolved and has a characteristic physical size of $\sim$ 1.3 AU and $\sim$ 9 AU at 2.2 μm and 11 μm respectively. This increase in apparent size towards longer wavelengths is much steeper than predicted by analytic disk models assuming power-law radial temperature distributions. For a detailed modeling of the interferometric data and the spectral energy distribution of MWC 147, we employ 2-D frequency-dependent radiation transfer simulations. This analysis shows that passive, irradiated Keplerian dust disks can easily fit the SED, but predict much lower visibilities than observed, so these models can clearly be ruled out. Models of a Keplerian disk with emission from an inner gaseous accretion disk (inside the dust sublimation zone), however, yield a good fit of the SED and simultaneously reproduce the observed near- and mid-infrared visibilities reasonably well. We conclude that the near-infrared emission from MWC 147 is dominated by accretion luminosity emerging from an inner gaseous disk, while the mid-infrared emission also contains strong contributions from the passive, irradiated dust disk.

1. Introduction

The spatial and temperature structure of the circumstellar material around Herbig Ae/Be stars, i.e. intermediate-mass pre-main sequence stars, is still a matter of debate. Until recently, the spatial scales of the inner circumstellar environment (less than a few AU, corresponding to < 0.1 arcsecond) were not accessible to optical and infrared imaging observations, and conclusions drawn on the spatial distribution of the circumstellar material were, in most cases, entirely based on the modeling of the spectral energy distribution (SED). However, as demonstrated by Men'shchikov & Henning (1997) and others, these SED model fits are highly ambiguous, and only the combination of SED modeling with high-resolution imaging can provide crucial constraints on the real geometry of the circumstellar matter. Since these ambiguities concern not only the disk geometry, but also the general nature of the disk (e.g. actively accreting vs. passive irradiated disks), high angular resolution observations are indispensable for obtaining more physical insight.

In recent years, long-baseline interferometry at infrared wavelengths made important contributions for a better understanding of the structure of the circumstellar material around young stars. A near-infrared (NIR) survey performed by Millan-Gabet, Schloerb & Traub (2001) with the IOTA interferometer showed that the NIR continuum emission is best described by ring-like geometries rather than with the "classical" optically thick, geometrically thin accretion disk models (e.g., Lynden-Bell & Pringle 1974; Hillenbrand et al. 1992). A correlation between the NIR size and the stellar luminosity was found (see Monnier & Millan-Gabet 2002), which suggests that the NIR continuum emission mainly traces hot dust at the inner sublimation radius. This observational result also stimulated theoretical work, especially for passive irradiated circumstellar disks, e.g. by Natta et al. (2001) and Dullemond, Dominik & Natta (2001). These models reproduce the ring-like morphology by introducing puffed-up inner rims for the circumstellar dust disk.

However, for some of the more luminous Herbig Be stars, deviations from the simple $R \propto L^{1/2}$ size-luminosity relation were found: the characteristic sizes of these objects are considerably smaller than the dust sublimation radius expected from the stellar parameters. Monnier & Millan-Gabet (2002) suggested that this might be due to the presence of an inner gaseous disk, which could shield the dust disk from the strong stellar ultraviolet radiation. Since this shielding would be most efficient for hot stars, it would allow the inner rim of the dust disk around B-type stars to exist closer to the star. Several subsequent studies (e.g., Eisner et al. 2004; Monnier et al. 2005) favored accretion disk models in which thermal emission from hot gas in the innermost disk regions (inside the dust sublimation radius) contributes significantly to the observed NIR flux.

Whereas most existing infrared interferometric studies on young stars were performed at NIR wavelengths (H and K-band), some objects were observed in the mid-infrared (MIR) band (e.g., Leinert et al. 2004; Preibisch et al. 2006). In contrast to the NIR band, which traces only the hottest dust close to the sublimation radius, the MIR regime is also sensitive to the warm dust at distances of a few 10 AU from the star. The combination of NIR *and* MIR interferometry can thus yield comprehensive information on the circumstellar material on spatial scales ranging from less than 1 AU to several 10 AU.

Furthermore, the latest generation of interferometric instruments provide also spectroscopic capabilities. Spectrally dispersed interferograms allow to derive visibilities as a function of wavelength. As circumstellar disks exhibit a temperature gradient, different wavelengths channels trace different spatial regions, and thus the spectro-interferometric measurements provide not only information about the density distribution of the circumstellar material, but also yield constrains on the temperature distribution in the disk.

2. Infrared Interferometry of MWC 147

MWC 147 is an intermediate-mass pre-main sequence star located in the Monoceros OB1 association at a distance of ~ 800 pc. For our modeling, we adopted the stellar parameters by Hernández et al. (2004), i.e. a spectral type of B6, $L_\star = 1\,550\ L_\odot$, $M_\star = 6.6\,M_\odot$, and $R_\star = 6.63\ R_\odot$. The object shows a strong infrared excess of about 6 mag at mid-infrared wavelengths, demonstrating the

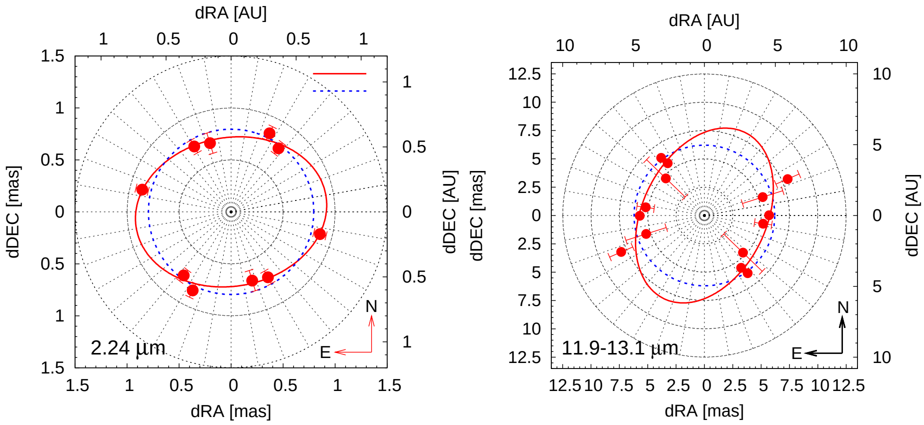

Figure 1. Polar diagram showing the best-fit circular (dotted line) and elliptical (solid line) geometries. To derive the characteristic object size along different PAs (dots with errorbars), we fitted ring profiles to the PTI K-band visibilities (left panel) and to MIDI visibilities (right panel).

presence of circumstellar material. Numerous observational results strongly suggest the presence of a massive circumstellar disk around MWC 147. Hillenbrand et al. (1992) fitted the spectral energy distribution of MWC 147 with a model for a massive accretion disk and estimated an accretion rate of $10^{-5}\,M_{\odot}\,\mathrm{yr}^{-1}$.

First infrared interferometric observations of MWC 147 were performed by Akeson et al. (2000) with the Palomar Testbed Interferometer (PTI) and revealed that the K-band size of this object is surprisingly compact (2.28 mas = 0.7 AU, uniform disk diameter). In order to investigate this object in more detail, we observed MWC 147 with the interferometric instruments MIDI and AMBER at the ESO Very Large Telescope Interferometer (VLTI). With MIDI we obtained 7 individual interferometric measurements at different baselines and position angles; these data cover the $8 - 13\,\mu$m wavelength band with a spectral resolution of $\lambda/\delta\lambda \approx 30$. With AMBER, one measurement was obtained, covering the $2.0 - 2.4\,\mu$m wavelength band at spectral resolution $\lambda/\delta\lambda \approx 35$. The visibilities derived from the AMBER data agree quite well to PTI data at similar baseline length and position angle. In all these measurements the resulting visibilities are significantly below 1, showing that the infrared emission is clearly resolved. All details of the observations and data analysis are described in Kraus, Preibisch, & Ohnaka (2007).

The most basic kind of interpretation of the interferometric data is to estimate characteristic sizes of the emitting region by comparing the observed visibilities to simple analytic intensity profiles, such as Gaussian or ring-like brightness distributions. In Fig. 1 we show the derived diameters for the PTI and the MIDI data as a function of position angle. The data indicate that the emitting region is *not* circular symmetric but somewhat elongated, what seems to suggest a flattened, e.g. disk-like geometry. However, the rather large uncertainties of the visibilities prevent us from deriving strong constraints on the level of ellipticity and the orientation angle.

An immediately very interesting result of this analysis is the remarkably small derived characteristic size for the NIR emission of about 0.7 AU; this is considerably smaller than the expected dust sublimation radius of about 2.7 AU based on the stellar parameters. Another interesting aspect is the large difference between the derived size in the NIR (~ 0.7 AU) and in the MIR (~ 4.5 AU). In order to see whether this strong increase in the observed size can be understood in the context of frequently used analytic accretion disk models, we compared the interferometric data to predictions from models of passive irradiated circumstellar disks as well as of active viscously accreting disks (Lynden-Bell & Pringle 1974). This analysis showed that none of the considered analytic models can reproduce the measured NIR and MIR-sizes simultaneously; models that reproduce the NIR size predict too small MIR sizes, while models that reproduce the MIR size predict too large NIR sizes. The analytic models cannot explain the observed strong increase in the characteristic size from the NIR to the MIR. This result and the strong discrepancy between the characteristic size and the expected dust sublimation radius shows that a more detailed modeling of the interferometric data is necessary in order to get valid information about the inner circumstellar environment of MWC 147. This was the motivation for our radiative transfer modeling described in the next section.

3. 2-D radiative transfer modeling

For our modeling of the interferometric data on MWC 147 we employed the radiative transfer code *mcsim_mpi* (Ohnaka et al. 2006), which solves the radiative transfer problem self-consistently using a Monte Carlo approach. For each radiative transfer model, we first checked the agreement with the SED of MWC 147, which we constrain using an archival *Spitzer*-IRS spectrum as well as photometric data from the literature. Then, a ray-trace program was used to compute synthetic images for each model and for any wavelength of interest. Finally, visibilities were computed from the simulated images for the points of the *uv*-plane covered by the data. Both the disk inclination as well as its orientation on the sky were treated as free parameters and varied in order to find the best agreement with the spectro-interferometric visibilities. All details of the modeling are described in Kraus, Preibisch, & Ohnaka (2007).

The dust density distribution in our models resembles a flared, Keplerian rotating disk with puffed-up inner rim, as parameterized by Dullemond, Dominik & Natta (2001) and extends from the dust sublimation radius (at ~ 2.7 AU, assuming $T_{\rm subl} = 1500$ K) to 100 AU. The radial density distribution was chosen according to $\rho(r) \propto r^{-3/2}$ and the disk flaring index $\beta = 1.175$. In order to reproduce the shape of the SED in the far-infrared regime, we found that, in addition to the disk, an extended envelope is required, for which we use a density distribution of the form $\rho(r) \propto r^{-1/2}$. The presence of such an envelope is also supported by mid-infrared imaging by Polomski et al. (2002), which revealed an extended, elongated structure.

Figure 2 shows model images, the SED, as well as the visibilities corresponding to the model of a passive, irradiated accretion disk. The predicted model visibilities (especially in the NIR, but also, to a lower degree, in the MIR) for this model are much smaller than the measured visibilities. We conclude that although passive irradiated circumstellar disk models are able to reproduce the SED of MWC 147, these models are in strong conflict with the interferometric

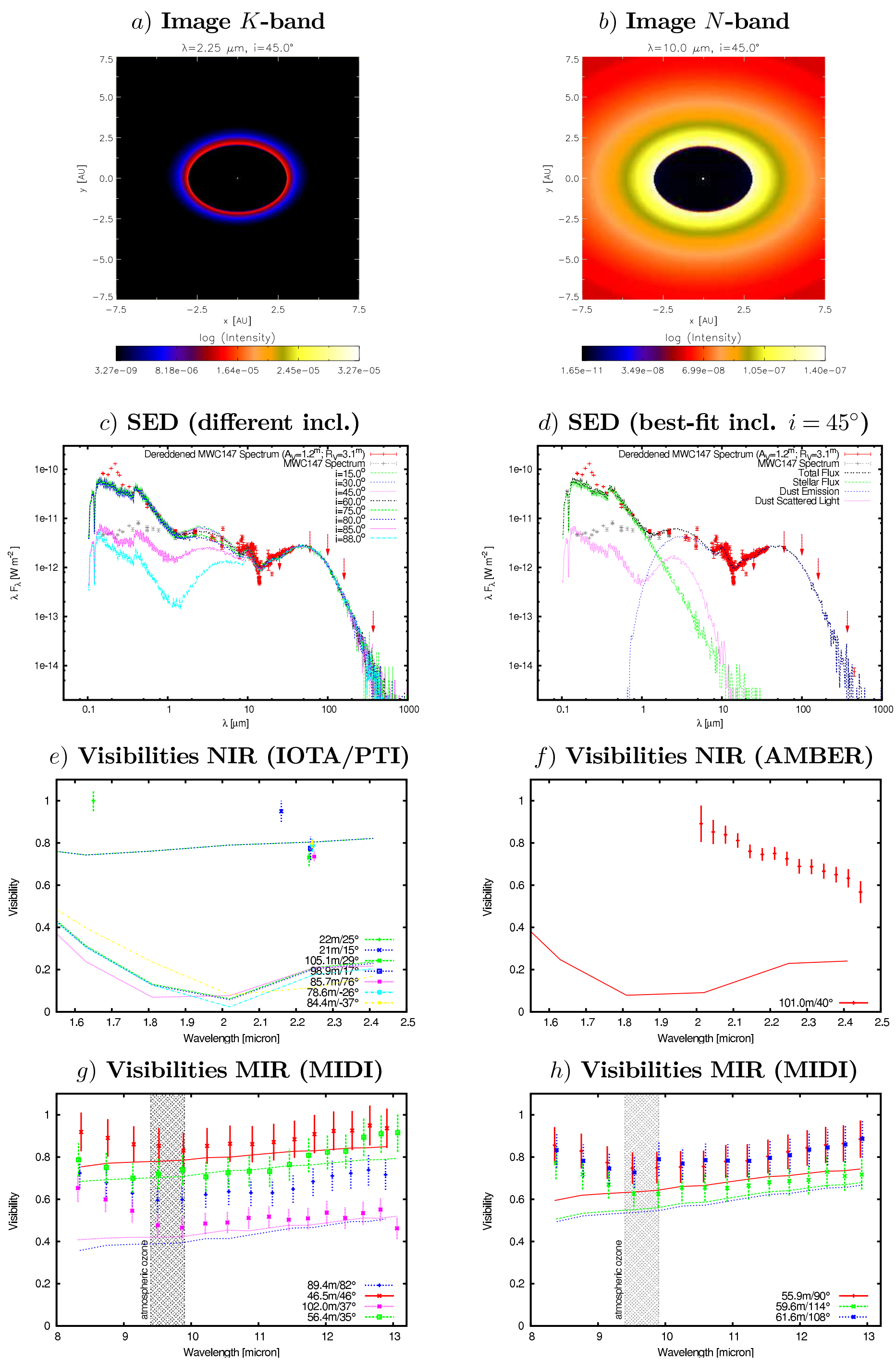

Figure 2. Best-fit radiative transfer model assuming a flared Keplerian disk geometry. This model results in a poor χ^2_r of 42. Panels *a*) and *b*) show the ray-traced images for two representative wavelengths (2.25 μm and 10.0 μm), *c*) shows the SED for various inclination angles, whereas *d*) gives the SED for the best-fit inclination angle (45°). Panels *e*) to *h*) show the observed and the model NIR and MIR visibilities.

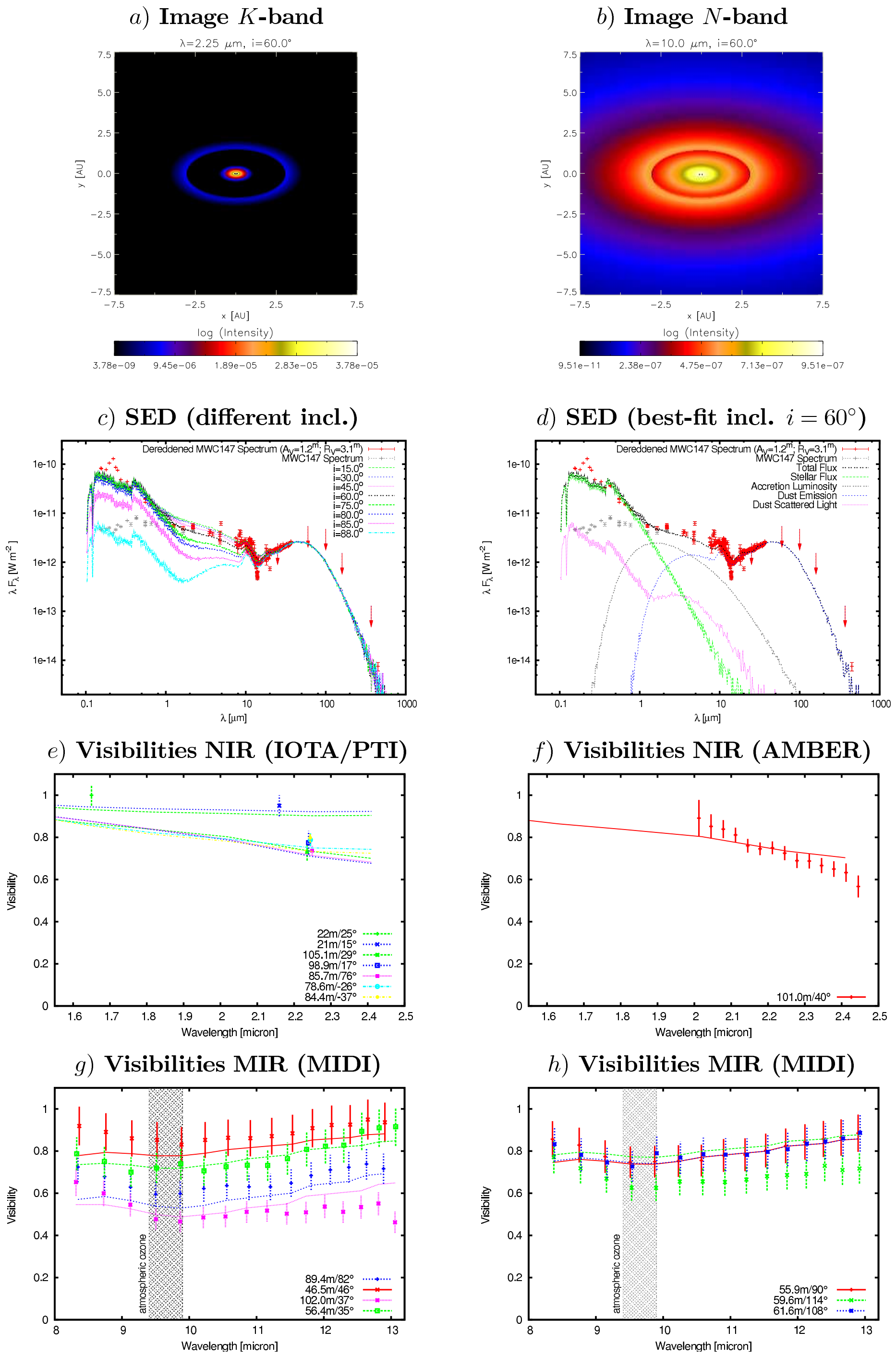

Figure 3. As Fig. 2, but for our best-fit model of a flared Keplerian disk plus emission from hot gas located inside the dust sublimation radius. With $\chi_r^2 = 1.26$ (inclination 60°), this model fits our spectro-interferometric data much better than the model without the inner gas emission (Fig. 2).

measurements, resulting in a very poor fit ($\chi_r^2 \approx 43$) to the combined visibility and SED data.

The discrepancy between model and data is related to the usual assumption that the observed infrared emission originates almost entirely from dust; any emission from the inner, dust-free gaseous part of the disk, at radii smaller than the dust sublimation radius, is usually assumed to be negligible. However, the viscous dissipation of energy in the inner dust-free gaseous parts of active accretion disks can heat the gas to high temperatures and may, under certain circumstances, give rise to significant amounts of infrared emission (e.g., Muzerolle et al. 2004). The inner edge of this gas accretion disk is expected to be located a few stellar radii above the stellar surface, where the gas is thought to be channeled towards the star via magnetospheric accretion columns. While the magnetospheric accretion columns are too small to be resolved in our interferometric data (3 $R_\star$ correspond to 0.09 AU or 0.12 mas, whereas the interferometric angular resolution at $2\,\mu$m and for a baseline of 100 m is ~ 4 mas), infrared emission from hot gas inside the dust sublimation radius may explain why the observed characteristic size of the NIR emission is smaller than the dust sublimation radius.

To explore this possibility in more detail, we included gas emission in our model. As MWC 147 is a quite strong accretor with an estimated accretion rate of $\dot{M}_{\rm acc} \approx 10^{-5}\ M_\odot\,{\rm yr}^{-1}$ (Hillenbrand et al. 1992), considerable infrared emission from the inner gaseous accretion disk can actually be expected. Muzerolle et al. (2004) found that, even for smaller accretion rates, the gaseous inner accretion disk can dominate the NIR emission. In these models, the inner gas disk is several times thinner than the puffed-up inner dust disk wall and is optically thick (both in radial as well as in the vertical direction).

In order to add the thermal emission from the inner gaseous disk to our radiative transfer models, we assume a radial temperature power-law as derived by Pringle (1981) for the gas component. As can be seen in Fig. 3, the inclusion of this inner gas emission to the model improves the agreement between model predictions and observed visibilities strongly. A good fit ($\chi_r^2 = 1.26$) is found with a model of a flared dust disk with inclination angle $\sim 60°$ and extending out to 100 AU, and an inner gas disk with an accretion rate of $\dot{M}_{\rm acc} = 9 \times 10^{-6}\ M_\odot\,{\rm yr}^{-1}$.

4. Summary and conclusions

Our infrared long-baseline interferometric observations of MWC 147 constrain, for the first time, the inner circumstellar environment around a Herbig Be star over the wavelength range from 2 to 13 μm. We measure a strong increase of the apparent size with wavelength, with a slope much steeper than predicted by the commonly used analytic temperature power-law models. To test whether more realistic physical models of the circumstellar dust environment yield better agreement, we employed 2-D radiative transfer modeling. These models include an dust disk embedded in an extended dust envelope, and were used to simultaneously fit the SED and the spectro-interferometric observables. While models of passive, irradiated disks are able to reproduce the SED, they are in strong conflict with the interferometric observables, significantly overestimating the size of both the NIR and MIR emission. Adding an inner gaseous accretion disk component to the model resolves the discrepancies and provides good agreement between the model predictions and the data.

Our study demonstrates that the spectro-interferometric capabilities of the latest generation of infrared long-baseline interferometers are very well suited to probe directly the geometry and temperature of the inner accretion disks around young stars and to disentangle individual emission components. The recent instrumental improvements of interferometers such as the VLTI do already now allow even more detailed studies, which can provide key glimpses into the inner circumstellar environment of young stellar objects. In the very near future, it will be possible to obtain interferometric data sets which allow the reconstruction of true images of young stellar objects with spatial resolution below one AU; this will provide unprecedented insight into the structure of the innermost circumstellar environment and strongly advance our understanding of accretion disks of young stars.

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