Studying the innermost AU of YSO accretion disks with VLTI spectro-interferometry

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Abstract. Accretion and outflow processes are of fundamental importance for our understanding of the formation of stars and planetary systems. Until recently, the innermost AU around young stars, where these processes are believed to take place, were not accessible to optical and infrared imaging observations. Therefore, most conclusions on the spatial distribution of the circumstellar dust and gas were drawn entirely based on the modeling of the spectral energy distribution and the fitting of line profiles. Here I present some recent investigations in which we employed ESO's Very Large Telescope Interferometer to spatially resolve the inner disk regions around several Herbig Ae/Be stars. In one study, we combined, for the first time, near- and mid-infrared interferometry on a Herbig star, which allows us to constrain not only the disk geometry, but also its radial disk temperature law, revealing the presence of hot gas inside of the dust sublimation radius. In the second study, we used the spectro-interferometric capabilities of the VLTI/AMBER instrument to investigate the spatial origin of the Br$\gamma$ hydrogen line emission, finding evidence both for mass infall and mass outflow.

1. Introduction

Herbig Ae/Be stars are intermediate-mass pre-main-sequence stars, which are still accreting material from their environment, likely from a circumstellar disk composed of dust and gas (Fig. 1). While the thermal emission from the dust disk is likely to be the dominant contributor to the infrared excess emission observed towards young stellar objects (YSO), it is believed that the dust content makes up only a small fraction of the total mass of the system. 99% of the mass is likely contributed by gas, in particular hydrogen, and can mainly be traced by spectral lines, which for pre-main-sequence stars are often found in emission. While some information about the kinematics of the gas can already be extracted from the line profile, the spatial origin of the gas emission and the physical processes it traces are still strongly debated.

Until recently, the spatial scales of the inner circumstellar environment (a few AU, corresponding to $\lesssim 0.1$ 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) and the interpretation of line profile shape. Therefore, to achieve substantially new constraints, this modeling has to be complemented with spatially resolved information as provided by infrared long-baseline interferometry.

Here I present two recent studies, in which we use ESO's Very Large Telescope Interferometer (VLTI) to investigate both the structure of the continuum-emitting disk, as well as the origin of the Br$\gamma$ line emission tracing the hydrogen gas component. The VLTI instruments AMBER
within the disk. In the second study we use mynq’s medium spectral resolution mode to investigate the near to mid-infrared geometry of the accretion disk around the Herbig Be star MWC 147, providing important information about the temperature distribution within the disk. In the second study (Sect. 3) we use AMBER’s medium spectral resolution mode, $R = \lambda/\Delta \lambda = 1500$, to resolve the Brγ-line emitting region of a sample of five Herbig Ae/Be stars, likely tracing gas which is just accreted onto the star through magnetospheric accretion columns or ejected from the star/disk system through an outflowing wind.

2. Studying the geometry and temperature structure of the active inner accretion disk around MWC 147

Various authors attempted to constrain the distribution of the circumstellar matter using SED model fitting, assuming such different geometries as optically thick accretion disks [1], optically thin spherical envelopes [2], envelopes with bipolar outflow cavities [3], or combinations of disk and halo geometries [4]. However, as demonstrated by Men’shchikov & Henning [5] 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. In particular, these ambiguities concern not only the disk geometry, but also the general disk properties (e.g. actively accreting vs. passive irradiated disk).

For our detailed study we selected the Herbig Be star MWC 147, which is located at a distance of 800 pc in Monoceros, and adopt the stellar parameters by Hernández et al. [6], namely a spectral type of B6, $L = 1550 L_\odot$, $M = 6.6 M_\odot$, and $R = 6.63 R_\odot$. The object shows a strong infrared excess of about 6 mag at mid-infrared wavelengths, demonstrating the presence of circumstellar material. Numerous recent observational results strongly suggest the presence of a massive circumstellar disk around MWC 147: Hillenbrand et al. [1] fitted the spectral energy distribution of MWC 147 with a model assuming a massive accretion disk and estimated an accretion rate of $10^{-5} M_\odot \text{yr}^{-1}$. First infrared interferometric observations were presented by Akeson et al. [7] and revealed that the K-band size is surprisingly compact (2.28 mas = 0.7 AU, uniform disk diameter).

We observed MWC 147 with VLTI UT baseline lengths ranging from 39 to 102 m and obtained seven measurements using the MIDI instrument and one AMBER observation. While the
Figure 2. Comparing the wavelength-dependent disk size of MWC 147 (as derived from one of our AMBER+MIDI measurements) with the wavelength-dependent disk size predicted by standard temperature power-law disk models, we find that these models cannot reproduce our measurements. In this figure, the disk model was scaled to match the measured MIR size.

AMBER observation around \( \sim 2 \mu m \) is most sensitive to the thermal emission from hot material located at the dust sublimation radius \( (T \approx 1500 \text{ K, a few AU from the star}) \), the MIDI measurements \( (\sim 10 \mu m) \) trace also dust at significantly lower temperatures \( (\text{down to } \sim 300 \text{ K}) \), located a few 10 AU from the star.

We find that the emission from MWC 147 is clearly resolved and has a characteristic physical size of \( \sim 1.3 \text{ AU and } 9 \text{ AU at } 2.2 \mu m \) and \( 11 \mu m \) respectively. As a first step of analysis, we compared the interferometric data to commonly used analytic disk models. Using the assumption that each disk annulus radiates as a blackbody, we can compute the wavelength-dependence of the disk size corresponding to these analytic models and find that the increase in apparent disk size towards longer wavelengths is much steeper than predicted by analytic disk models assuming power-law radial temperature distributions of viscous or irradiated disks \( T(r) \propto r^{-\alpha} \) with \( \alpha = 3/4 \) or \( 1/2 \), see Fig. 2.

Therefore, we applied a more sophisticated modeling approach using the \textit{mcsim.mpi} 2-D radiative transfer code (Ohnaka et al. [8]). The dust density distribution of the accretion disk in our models resembles a flared, Keplerian-rotating disk with a radial density distribution \( \rho(r) \propto r^{-3/2} \), extending from the dust sublimation radius to 100 AU. In order to reproduce the shape of the SED, we find that, in addition to the disk, an extended envelope is required, for which we use the radial density distribution \( \rho(r) \propto r^{-1/2} \). For each model, we first check the agreement with the SED of MWC 147 and then fit the spectro-interferometric visibilities (see Kraus et al. [9]).

Our analysis shows that passive irradiated Keplerian disks can easily fit the SED, but predict much lower NIR visibilities than observed (Fig. 3), such that these models can clearly be ruled out. Models of a Keplerian disk with optically thick gas emission from an active gaseous disk (inside the dust sublimation zone), however, yield a good fit of the SED and simultaneously reproduce the absolute level and the spectral dependence of the NIR and MIR visibilities (Fig. 4). We conclude that the NIR continuum emission from MWC 147 is dominated by accretion luminosity emerging from an optically thick inner gaseous disk, while the MIR emission also contains contributions from the outer, irradiated dust disk.
Figure 3. Best-fit radiative transfer model for MWC 147 assuming a passive, irradiated dust disk geometry. Panels a) to c) show the dust density and temperature distribution, and SED, respectively. In Panels d) to g) we show ray-traced images for some wavelengths covered by our interferometric data, while h) to i) show the observed and the model NIR and MIR visibilities. This model results in a poor $\chi^2_r$ of 25.

To summarize, our VLTI 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 $\mu$m. We find evidence that the NIR emission of MWC 147 is dominated by the emission from optically-thick gas located inside the dust sublimation radius, while the MIR also contains contributions from the outer, irradiated dust disk.
3. Resolving the Br\(\gamma\) hydrogen line-emitting region of five Herbig Ae/Be stars

Compared to the structure of the continuum-emitting disk, even less is known about the origin of the line-emission observed towards YSOs. For example, it has been proposed that hydrogen recombination lines, such as the Br\(\gamma\) 2.166 µm line, might trace the following processes (Fig. 1):

(a) **Stellar winds**[10],
(b) **Stellar-field driven winds (X-winds)** launched from the inner edge of the disk [11],
(c) **Disk-field driven winds (disk winds)** launched from the disk [12],
(d) **Magnetospheric accretion** of matter onto the star [13], or
(e) **Optically-thin gas** located inside of the dust sublimation radius [14].

Since each of these processes is associated with different spatial scales, spatially resolved...
observations are required in order to discern between the large number of proposed line-emitting mechanisms. Until now, three studies investigated the geometry of the Brγ line-emitting region using either the VLTI or the Keck Interferometer. First AMBER observations of the Herbig Be star MWC 297 have shown that the Brγ-emitting region around this star is more extended than the continuum region (Malbet et al. [15]). Surprisingly, observations on the less luminous Herbig Ae star HD 104237 did not show any change in visibility along the Brγ line (Tatulli et al. [16]). Finally, Eisner [17] found a visibility increase within the Brγ line for the Herbig Ae star MWC 480.

Since each of these earlier studies focused on individual objects and was therefore not able to investigate the dependence of the line-emitting mechanism on stellar or environmental properties, we performed recently the first spectro-interferometric study on a larger sample of HAeBe stars. We obtained new AMBER UT observations on the Herbig Ae stars HD 104237 and MWC 275 as well as on the Herbig Be stars HD 98922 and V921 Sco, including for our analysis also the two archival AMBER data sets on MWC 297 [15] and HD 104237 [16]. With baseline lengths between 35 and 74 m and a spectral resolution $R = 1500$, we spatially and spectrally resolved the inner environment in the Brγ emission line as well as in the adjacent continuum. The spectro-interferometric data is supplemented by archival and new VLT/ISAAC spectroscopy.

For each spectral channel of our AMBER interferograms we derive a value for the visibility amplitude (see Fig. 5), providing spatial information about the brightness distribution contributing to this spectral channel. Within the Brγ line, the flux within a spectral channel is composed of the line emission plus the underlying continuum contribution. To model this visibility data, the measured continuum+line visibility has to be corrected for the continuum contribution, yielding the visibility of the pure line-emitting region.

Assuming ring/ellipse geometries for the emitting region, we derive the characteristic size of

![Figure 5](image)

**Figure 5.** Brγ spectra (upper row) and wavelength-dependent visibilities (lower row) extracted from our AMBER and ISAAC data.
the continuum- and line-emitting regions (Fig. 6) and compare them to the spatial scale predicted for mass infall and outflow scenarios. In our sample of two Herbig Ae and three Herbig Be stars, we find evidence for at least two line-emitting mechanisms, one resulting in a very compact \(Br_\gamma\)-emitting region \(R_{Br_\gamma}/R_{cont} \lesssim 0.3\), HD 98922, likely tracing magnetospheric accretion) and another resulting in a rather extended \(Br_\gamma\)-emitting region \(R_{Br_\gamma}/R_{cont} \approx 0.7 - 1.4\), HD 104237, MWC 275, V921 Sco, and MWC 297, likely tracing a stellar wind or disk wind).

One particularly intriguing result of our investigation is that the size of the \(Br_\gamma\)-emitting region seems to correlate with the morphology of the hydrogen line profile (Fig. 7). Since the spectral resolution of our ISAAC spectra \((R = 8,900)\) did not suffice to properly resolve the \(Br_\gamma\)-line profiles, we compared the measured \(Br_\gamma\) sizes instead with the morphology of the \(H\alpha\)-line from literature and found that stars with P-Cygni \(H\alpha\)-line profile show a particularly compact \(Br_\gamma\)-emitting region, while stars with double- or single-peaked line profile show a significantly more extended line-emitting region (Fig. 7).

During the last decade, numerous spectroscopic studies found that the \(Br_\gamma\)-line luminosity correlates with the accretion luminosity as determined from UV veiling \((L_{Br_\gamma}-L_{acc} \text{ relation, e.g.}\ [18, 19])\), which lead to the suggestion that this line might be a direct tracer of magnetospheric accretion [13]. Being applicable even in regions of high extinction and for very low accretion luminosities, this correlation is also of considerable practical importance as an estimator for the mass accretion rate (e.g. [20]). In this context, our finding that the \(Br_\gamma\)-line can trace both, mass infall and outflow, is very surprising and implies, that, at least for some HAEBe stars, \(Br_\gamma\)

![Figure 6](image)

**Figure 6.** Using the AMBER visibilities shown in Fig. 5 and assuming a ring-shaped geometry we derive the characteristic size of the continuum- (black circle) and \(Br_\gamma\) line- (red circle) emitting region for the five stars in our sample.

![Figure 7](image)

**Figure 7.** We find that the size of the \(Br_\gamma\)-emitting region seems to be correlated with the \(H\alpha\) line profile, providing new constraints for theoretical accretion and wind models.
is not a primary tracer of accretion, but indirectly linked to the accretion rate, e.g. via accretion-driven mass loss. Taking this ambivalent origin of the line emission and the tight correlation of the luminosity of this line with the mass accretion rate into account therefore suggests a quantitative connection between the accretion and outflow processes in YSOs. This conclusion is in good agreement with the results from earlier observational studies, which investigated the accretion-outflow connection using only spectroscopic diagnostics (e.g. Cabrit et al. [21]).

4. Conclusions

We have presented two recent case studies, in which we employed the VLTI/AMBER and MIDI instruments to study important accompaniments of the star formation process, including the structure of circumstellar disks (Sect. 2) and the accretion or outflow processes which feed the forming star with material and remove excess angular momentum from the system (Sect. 3). This kind of spectro-interferometric investigations on YSOs might also benefit substantially from the proposed 2nd generation VLTI instruments, such as GRAVITY, MATISSE, and VSI, increasing not only the number of recorded baselines, but also expanding the spectral coverage to the $J$, $H$, $K$, $L$, $M$ and $N$ bands.

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