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INFRARED INTERFEROMETRY OF YOUNG STELLAR OBJECTS

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RESUMEN

Discos circunestelares alrededor de objetos estelares jovenes desempeñan un rol fundamental en el proceso de formación de estrellas y proporcionan una etapa para la formación de planetas. Desde recientemente, la interferometría infrarroja proporciona la resolución espacial requerida para estudiar directamente la distribución del gas y del polvo en la Unidad astronómica más cercana alrededor de la estrella en formación. Presentamos investigaciones recientes en las cuales empleamos el VLTI e interferométros en infrarrojo cercano y lejano AMBER y MIDI para restringir la geometría y condiciones físicas de discos alrededor de estrellas Herbig Ae/Be y estudiar los procesos del acreción y decreción que ocurren cerca de la estrella central.

ABSTRACT

The circumstellar disks around young stellar objects play a key role in the formation process of stars and provide the stage for planet formation. Since recently, infrared interferometry provides the spatial resolution required to directly study the distribution of the gas and dust in the innermost AU around the forming star. We present recent investigations in which we employed the VLTI and its near- and mid-infrared interferometric instruments AMBER and MIDI to constrain the geometry and physical conditions of the disks around Herbig Ae/Be stars and to study the accretion and outflow processes taking place close to the central star.

Key Words: accretion, accretion disks — stars: pre-main sequence — stars: winds, outflows — techniques: interferometric

1. INTRODUCTION

The circumstellar disks around young stars are essential ingredients of the star and planet formation process. Through the process of viscous friction, the disks redistribute the excess angular momentum and allow the infall of further material and the growth of the star to its final mass. In this paper, we present three recent studies in which we employed infrared interferometry to study the inner (AU-scale) circumstellar environment around hot young stars. Each of these studies focuses on different aspects of YSO research and employs different instruments and/or spectral modes, illustrating the fascinating observational opportunities provided by this new and quickly evolving technique.

2. DETECTION OF A HOT INNER GASEOUS COMPONENT IN A YSO ACCRETION DISK USING NIR/MIR INTERFEROMETRY

Near-infrared (NIR) broadband interferometric observations on large samples of intermediate-mass YSOs (Herbig Ae/Be stars) revealed a correlation between the size R of the NIR-emitting region and the stellar luminosity L, following roughly a $R \propto L^{1/2}$ law. This suggests that the NIR continuum emission mainly traces hot dust at the inner sublimation radius. However, for more luminous Herbig Be stars, the NIR-emitting structure often appears more compact than predicted by the size-luminosity relation (e.g. Monnier & Millan-Gabet 2002).

To further investigate the origin of the "undersized" Herbig Be star disks, we observed the B6-type star MWC 147 using the VLTI near-infrared instrument AMBER (operating between 1 and 2.5 μm) and the mid-infrared instrument MIDI (8–13 μm). While AMBER is mainly sensitive to the thermal emission from hot material located at the dust sublimation radius ($T \approx 1500$ K, a few AU from the star), the MIDI measurements also trace dust at significantly lower temperatures (down to ~ 300 K), located a few 10 AU from the star. In all measurements, the emission from MWC 147 is clearly resolved and has a characteristic physical size of ~ 1.3 AU and ~ 9 AU at 2.2 μm and 11 μm, respectively. For our physical interpretation, we applied 2-D radiative transfer simulations and modeled the dust density distribution corresponding to spherical shells, as well as passive and active accretion disks. Our analysis shows that spherical shells as well as passive irradiated Keplerian disks can easily fit the SED but predict much lower NIR visibilities than observed, so that these

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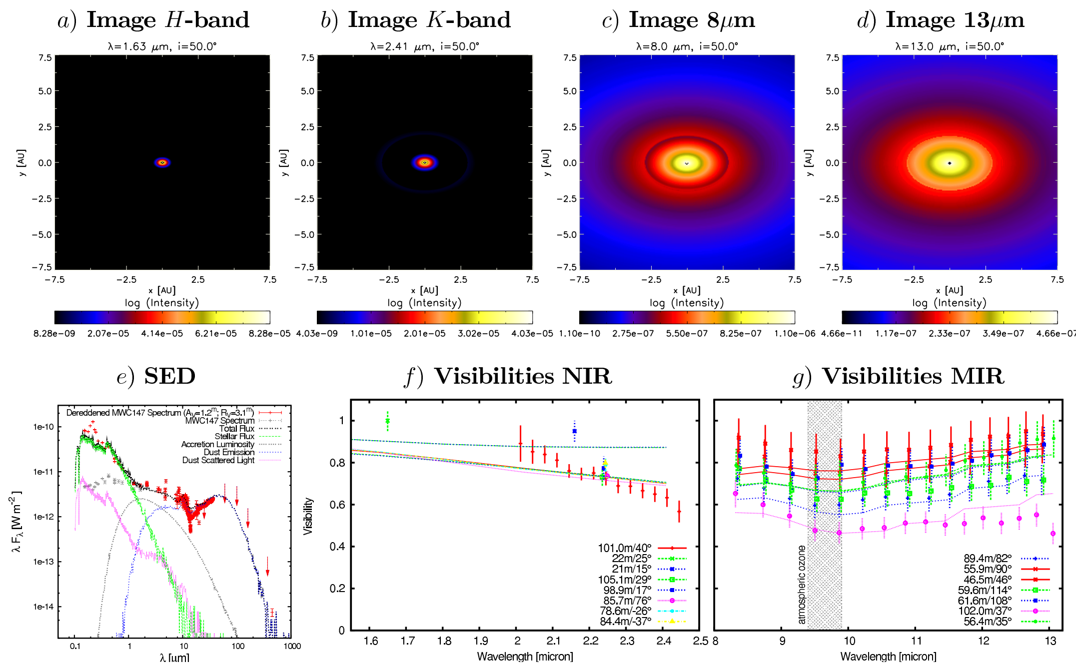

Fig. 1. In our study on MWC 147, we obtained AMBER and MIDI measurements (*f* and *g*), which could be well reproduced with a disk model incorporating an outer dust and an inner gaseous disk (see *a* to *d* for the images of our best-fit model). The model also fits the SED (*e*).

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 (Figure 1). 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 (Kraus et al. 2008a).

3. RESOLVING THE ACCRETION AND OUTFLOW-LAUNCHING REGION IN SPECTRAL LINES

To trace the accretion and outflow processes in YSOs, diagnostic lines, such as the Brγ 2.16 μm hydrogen recombination line, are widely used. However, due to a lack of spatial resolution, the origin of these lines and the involved physical processes are still not well known. Several models associating the line emission either with stellar winds, disk winds, collimated jets, magnetospheric accretion, or the presence of a gaseous inner disk have been proposed (see Figure 2, *right*). Since most of these processes are believed to take place on (sub-)AU scales, they were not accessible with direct imaging techniques until recently. Therefore, most earlier studies tried to constrain the spatial distribution and kinematics of the line-emitting gas from the shape of the line profiles. However, these line-profile-fitting techniques are known to be highly ambiguous. Infrared interferometry with high spatial resolution allows one to measure the extension and position of the line-emitting region relative to the continuum-emitting region and, thus, to discriminate between the scenarios discussed above.

We obtained AMBER UT observations with a spectral resolution of $R = 1\,500$ on two Herbig Ae (HD 104237, HD 163296) and two Herbig Be stars (HD 98922, V921 Sco) and also include archival data sets on MWC 297 (Malbet et al. 2007) and HD 104237 (Tatulli et al. 2007) for our analysis. For each spectral channel, we derive a value for the visibility amplitude, both in the Brγ emission line as well as in the adjacent continuum. Assuming ring/ellipse geometries for the emitting region, we derive the characteristic size of the continuum- and line-emitting regions (Figure 2, *left*) and compare them to the spatial scale predicted for mass infall and outflow scenarios. Using this procedure, we find evidence for at least two line-emitting mechanisms, one resulting in a very compact Brγ-emitting region ($R_{\mathrm{Br}\gamma}/R_{\mathrm{cont}} \lesssim 0.3$, HD 98922, likely tracing

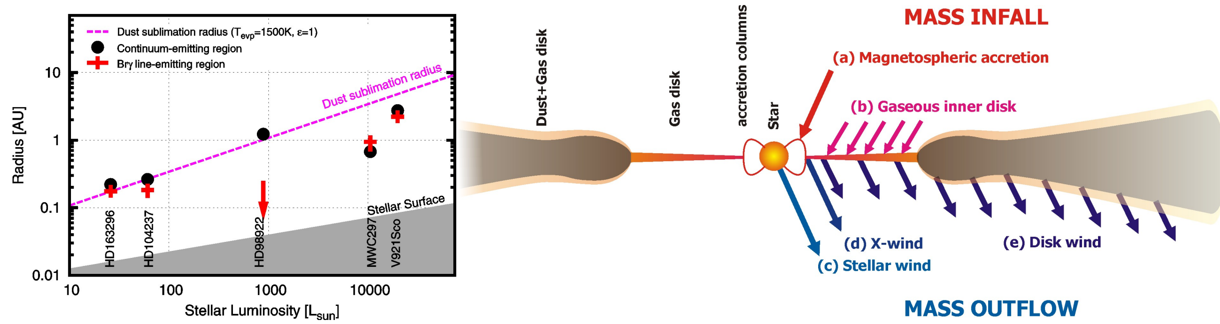

Fig. 2. *Right:* Illustration of scenarios which have been proposed for the origin of the line emission in Herbig Ae/Be stars. *Left:* Our AMBER observations constrain the size of the continuum- and Brγ-emitting region.

magnetospheric accretion) and another resulting in a rather extended Brγ-emitting region ($R_{\mathrm{Br}\gamma}/R_{\mathrm{cont}} \approx 0.7 - 1.4$, HD 104237, MWC 275, V921 Sco, and MWC 297), likely tracing a stellar wind or disk wind.

During the last decade, numerous spectroscopic studies found that the Brγ-line luminosity correlates with the accretion luminosity, as determined from UV veiling ($L_{\mathrm{Br}\gamma}$–L_{acc} relation, e.g. Muzerolle et al. 1998), which led to the suggestion that this line might be a direct tracer of magnetospheric accretion. In this context, our finding that the Brγ-line can trace both mass infall and outflow is very surprising and implies that, at least for some HAeBe stars, Brγ is not a *primary* tracer of accretion, but *indirectly linked* to the accretion rate, e.g. via accretion-driven mass loss (Kraus et al. 2008b).

4. TRACING THE DYNAMICAL ORBIT OF THE θ^1Ori C BINARY SYSTEM

Another important application of optical interferometry in the field of hot star research is the measurement of the dynamical orbit of close binary systems. When combined with radial velocity measurements, these orbits can be used to derive stellar masses, providing important input for the calibration of stellar evolutionary models of O-type stars.

A particularly interesting binary system is θ^1Ori C, located in the center of the famous Orion Nebula Cluster (ONC) and one of the youngest ($\lesssim 10^6$ yrs) and nearest ($d \sim 400-450$ pc) high-mass stars known. Since the discovery of the θ^1Ori C companion (Weigelt et al. 1999), we have traced the orbital motion of the system using bispectrum speckle interferometry at NIR (J, H, K-band) and visual wavelengths (B, V-band). Between January 2007 and March 2008, we obtained 13 VLTI/AMBER observations of θ^1Ori C, including observations on one UT and three AT configurations. Given the resulting good uv-coverage, we were able to reconstruct a model-independent aperture synthesis image showing the θ^1Ori C system with a resolution of ~ 2 mas (Kraus et al. 2009). To extract the astrometric information, we implemented an algorithm which fits closure phases and differential visibilities. Including all available astrometric measurements, we solved for the astrometric orbit of the system, yielding a short-period ($P \sim 11.2$ yrs), high-eccentricity ($e \sim 0.6$) orbit (Figure 3). From the orbital elements, we derived constraints on the system mass ($M_1 + M_2 = 47 \pm 4\ M_\odot$) and on the distance to the ONC (410 ± 20 pc). Combining our solution for the astrometric orbit with radial velocity measurements

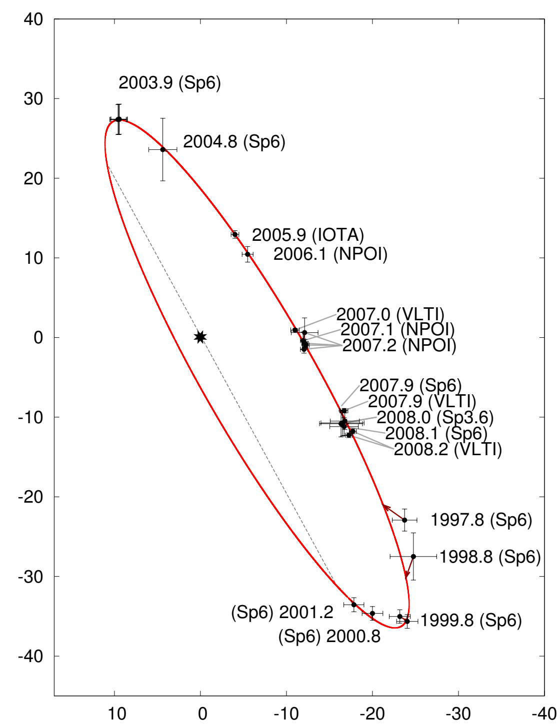

Fig. 3. Dynamical orbit of the θ^1Ori C binary system.

from the literature also constrains the mass ratio of the two stars ($M_2/M_1 = 0.23 \pm 0.05$) and, thus, the individual stellar masses (~ 39 and 8 $M_\odot$).

5. OUTLOOK

Spectro-interferometry now provides exciting new opportunities to study the disks around YSOs, allowing one to characterize the geometry of the continuum-emitting disk over a wide spectral range (§ 2) or to spatially resolve the emitting region of Doppler-broadened spectral lines (§ 3). Furthermore, by measuring the orbital motion of close binary stars, infrared interferometry can provide important information about the fundamental parameters of hot young stars such as θ^1Ori C (§ 4).

In the near future, spectro-interferometric investigations will dramatically benefit from the increased number of baselines (likely resulting in model-independent aperture synthesis images with high dynamic range) as well as from the gain in sensitivity provided by on- and off-axis fringe tracking (e.g. by VLTI/PRIMA) and an extended spectral coverage (e.g. L- and M-band for VLTI/MATISSE).

DISCUSSION

G. Meynet: *You mention that some Herbig stars have a radius for dust sublimation smaller than the other. You invoked the possibility that this may be due to the presence of gas inside the sublimation radius. Do we know why some stars have gas in that region and others not?* — In general, it is expected that all actively accreting Herbig Ae/Be stars should possess an inner gaseous disk. Infrared interferometry now allows us to directly detect these inner disks and to determine their contributions to the total near-infrared continuum emission. However, many more observations will be required to determine how the properties of the inner gaseous disk are linked, for instance, to the stellar parameters and the mass accretion rate.

C. Jones: *What are typical sizes of the inner gaseous regions you find for these stars?* — Even with baseline lengths of ~ 100 m, the inner gaseous disk could only be marginally resolved. Therefore, with the available data we can only put upper limits on the size of the gaseous disks.

D. Baade: *Where would you place the occurence of the hot inner gas disks of Herbig Be stars in an evolutionary context?* — I expect that the contributions from the hot inner gas dominate in the early, accretion-dominated phase.

A. Miroshnichenko: *I think that the correlation between the accretion luminosity and* Brγ *luminosity is not empirical, but rather model-dependent. Also, Herbig Be stars of different masses may have different ages and, therefore, different ratios of accretion and outflow.* — Thanks for this comment. To my knowledge, the authors who claimed an empirical correlation between the accretion luminosity and the Brγ luminosity estimated the accretion luminosity by modeling the UV veiling in T Tauri and Herbig Ae, which is believed to be the most direct tracer of the accretion rate. Of course, this method is also, to some degree, model-dependent.

J. Groh: *Would you have any estimate on the spectral type of the companion of θ^1 Ori C?* — In our 2007 paper, we modeled the wavelength-dependent flux ratio, yielding a rather high companion mass of $\sim$ 15 $M_\odot$. However, this method is associated with various observational uncertainties and depends on the assumed stellar atmosphere models. A more reliable estimate can now be extracted from the radial velocities, directly yielding the mass ratio ($M_2/M_1 = 0.23 \pm 0.05$). Accordingly, the companion mass should be closer to 8 $M_\odot$, corresponding to a spectral type of about B2.

R. Barbá: *The secondary in θ^1 Ori C could be a PMS star, thus, the IR fluxes should be larger than for a MS star with similar mass. So, my guess is that the secondary would be a PMS middle/late B star with 8 $M_\odot$.* — I agree, although it is not clear whether circumstellar material around the companion could survive in the presence of the strong stellar winds from the primary star.

H. Zinnecker: *Can you explain in a little more detail why you can get away with relative visibilities for the θ^1 Ori C system?* — The wavelength-differential visibilities and closure phase measured by AMBER allow one to sample the sinusoidal modulation, which is typical for wide binary sources such as θ^1Ori C. The information about the position of the binary is already encoded in the phase of this modulation, while the amplitude of the modulation is related to the flux ratio between the two components. Therefore, it is possible to extract the astrometric information using only differential observables.

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