SF2A 2008
C. Charbonnel, F. Combes and R. Samadi (eds)

PROBING THE HOT GAS IN YOUNG STELLAR OBJECTS WITH VLTI/AMBER

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Abstract. In this paper, I give a summary of the recent results obtained with AMBER on spectro-interferometric observations of Herbig Ae/Be stars. This summary is not exhaustive but representative of the unique capabilities of AMBER to probe the hot circumstellar gas, in addition to the usually observed dust near-infrared thermal emission.

1 Introduction

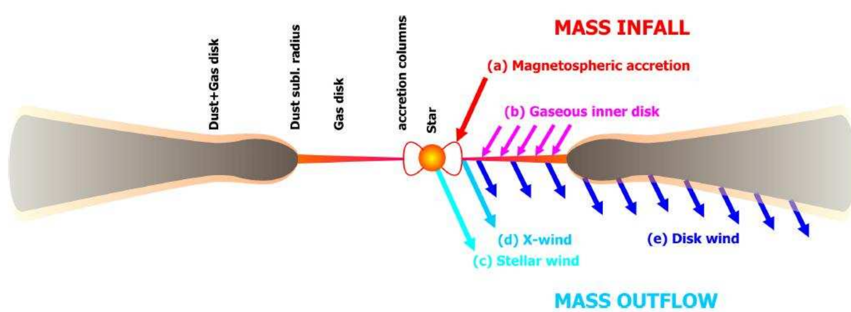

Fig. 1. Sketch of the inner environment around young stellar objects, from Kraus et al. (2008). See text for detailed description.

Observing the protoplanetary disks around young stars is a key issue to understand the first steps of planet formation mechanisms. Such processes are occurring in the very inner environment of the central star, at distances of a few Astronomical Units. The representation that we have today of this environment is sketched in Fig. 1, which is basically composed of i) magnetically-driven columns of gas accreting on the central star, ii) a gaseous dust-free rotating disk, iii) a dusty disk which inner rim is located at the dust sublimation radius; and iv) potentially outflowing winds.
Observational clues that we can obtain of the inner part of the protoplanetary disks are twofold:
- from their continuum infrared excess of the SED, that arises from the thermal emission of the circumstellar dust. It will give informations about the structure/geometry of the disk as well as about its dust grain composition (grain growth, radial/vertical distribution, mineralogy).
- from their infrared emission (/absorption) lines, in particular the hydrogen lines, that can originate from mainly three different mechanisms: i) magnetospheric accretion along the accreting columns of gas (Hartmann et al. 1994); ii) magnetically-driven outflows (Shu et al. 1994; Casse & Ferreira 2000); and/or from the rotating gaseous disk itself (Tambovtseva et al. 1999).

In order to characterize these mechanisms unambiguously, one needs both spatial and spectral resolution to localize and separate the continuum and line emission regions. At distances of the first stellar formation regions ($\sim$ 150pc), 1AU corresponds to a angular distance of $\sim$ 6mas, a resolution that only interferometric techniques

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can achieve. Furthermore, at such distances from the star, the temperature at the inner region of young stars is roughly between a few 100K and a few 1000K, that is radiating at near infrared wavelengths. As a result, near infrared spectro-interferometry which provides both the spatial and spectral resolution required at the desired wavelengths appears to be a technique perfectly suited to observe the inner environment of protoplanetary disks. In this instrumental context, we will focus here on the VLTI/AMBER recombiner which is so far the unique instrument that can simultaneously offer a proper spatial resolution (up to 2mas @ 2.2μm $\equiv$ 0.3AU @ 150pc), spectral coverage (K and H bands) together with a spectral resolution allowing to resolve the emission lines (R=1500).
In the following, we will illustrate how AMBER enables to probe the gas in YSOs giving two examples: in Section 2 by investigating the accretion/ejection phenomena in Herbig Ae/Be stars, and in Section 3 by probing the hot circumstellar gas around young stars.

2 The Origin of the Brγ emission in Herbig Ae/Be stars

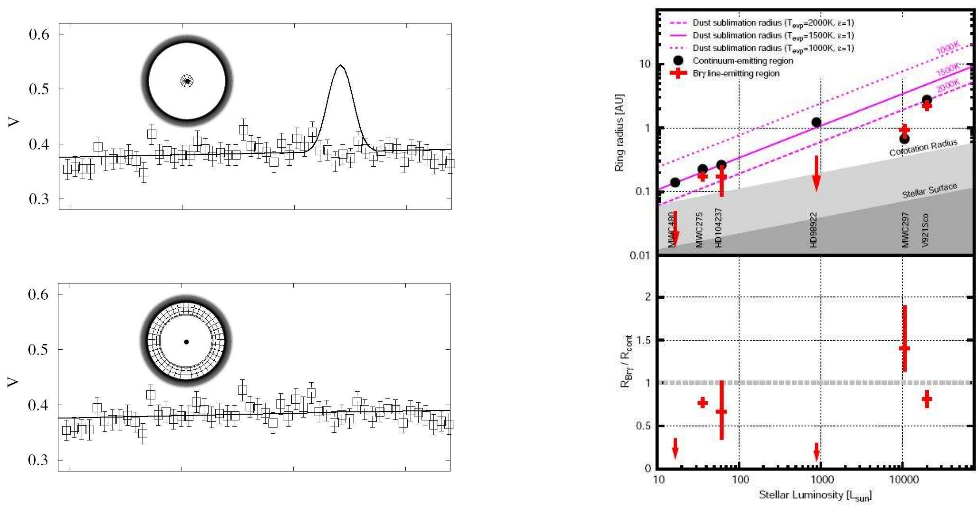

Fig. 2. Left: visibility around the Brγ line of HD104237 and superimposed magnetospheric-accretion (up) and wind (down) models, from Tatulli et al. (2007). Size of the Brγ region for 6 Herbig Ae/Be stars as a function of the star's luminosity, from Kraus et al. (2008).

From the first observation...: As summarized in previous Section, the origin of hydrogen emission lines in protoplanetary disks is still subject to debate. In order to disentangle between the possible scenarios, Tatulli et al. (2007) have used the VLTI/AMBER instrument to spatially and spectrally resolve for the first time the inner region of the Herbig Ae star HD104237 around its strong Brγ emission line. They have thus obtained visibility measurements in the Brγ line and in the adjacent continuum. The continuum was classically interpreted as arising from the inner rim of the dusty disk located at the sublimation radius. In the Brγ line however the visibility was same than in the continuum, leading them to conclude that the Brγ emission region presented, within the error bars, dimensions similar to that of the continuum one. This strong dimensional constraint enabled to unambiguously rule out the magnetospheric accretion (as well as the gaseous disk) scenario as responsible from the Brγ emission since it would have come from a much smaller region, located typically between the star and the corotation radius, and would have led to a significant increase of the visibility (see Fig. 2 (left, up)). Conversely, the behaviour of the visibility was compatible with the wind scenario, seen face-on as a ring of inner rim $R \sim 0.2$ to 0.5AU (see Fig. 2 (left, down)).

... to a systematic study: Since then, the increase in sensibility and precision of the instrument has recently allowed Kraus et al. (2008) to reproduce that type of analysis of a larger sample of 6 stars, as summarized in Fig. 2 (right). They hence shown that, if for two stars (HD98922, MWC480) the interferometric measurements were compatible with the magnetospheric-accretion for the origin of their Brγ emission, the wind scenario was favored for three of them (MWC275, MWC297, V921Sco) and also confirmed for HD104237. Taken statistically, these results are also interesting to analyze: first, the correlation suggested earlier by Eisner et al. (2007) between the origin of the Brγ emission and the star's luminosity is not observed; and most of all, at the contrary of TTauri stars for which the direct correlation between accretion and Brγ emission is well established, in Herbig Ae/Be stars we are mostly probing outflows phenomena from Brγ emission, this latter being probably in this case an indirect tracer of accretion through accretion-driven mass loss.

3 Probing the inner disk of gas

Whereas Brγ is a good tracer of whether magnetospheric accretion or outflowing winds, AMBER, by exploring other lines or by performing a two (H,K)-wavelengths analysis of the continuum, is also suited to directly probe the gas in the disk itself, as it is illustrated in the two following examples.

3.1 The hot molecular gas in 51 Oph

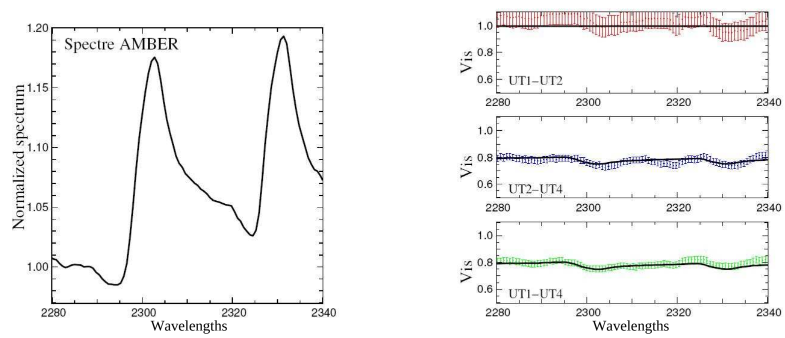

Fig. 3. AMBER spectrum of CO bandheads in 51 Oph (left) and measured visibilities (right), from Tatulli et al. (2008)

Tatulli et al. (2008) has recently presented the first interferometric observations at the 2.3μm CO overtone emission in the (B9) Be star 51 Oph, using the AMBER instrument (see Fig. 3). 51 Oph is indeed one of the very few young stars where this emission is strong enough to be observed with infrared spectro-interferometry (Thi el al. 2005; Berthoud 2008). Obtaining visibility on three baselines around the CO bandheads, they have shown for the first time that:
- the hot CO emission was resolved, located at a distance of 0.15AU from the star, thus in perfect agreement with the scenario in which the CO is emitted from the first AU of a rotating gaseous disk (Thi et al. 2005)
- the adjacent continuum is located at a distance of 0.25AU, that is too close to the star compared to the location of the sublimation radius, suggesting that i) the stellar light is shielded by the optically thick gas hence moving the sublimation radius closer to the star, and/or that ii) the hot gas inside the dust sublimation radius significantly contributes to the observed 2 μm emission (free-free emission).

3.2 Gas and dust in the inner disk of MWC 758

In this study, Isella et al. (2008) have emphasized the interest of simultaneously observed protoplanetary disks in both H and K band, showing that low spectral resolution (R=35) observations are also of interest to probe not only the dust but the gas in such objects. Indeed, if the K band will be mainly sensitive to the dust thermal emission at ~ 1500K, H band will probe an hotter and closer region in which the dust is likely to have sublimated, leaving a gaseous dust-free disk. They have demonstrated this point by observing the Herbig Ae star MWC758 with AMBER, obtaining visibilities and closure phases in H and K bands, as shown in Fig. 4 (left).
If the K band observations alone are well interpreted by the classical dusty puffed-up inner rim ($T_{sub} = 1400$K, $R_{in} = 0.34$AU), it fails to reproduce the H band observations for which the emission is less resolved than expected by this model. Furthermore, with this model, the SED can be not fitted successfully, showing a lack of energy in the H band. Conversely, by adding to the model the presence of an unresolved hotter component (of $T_g = 2500$K), they managed to reproduce both the H and K bands measurements jointly. Note that this

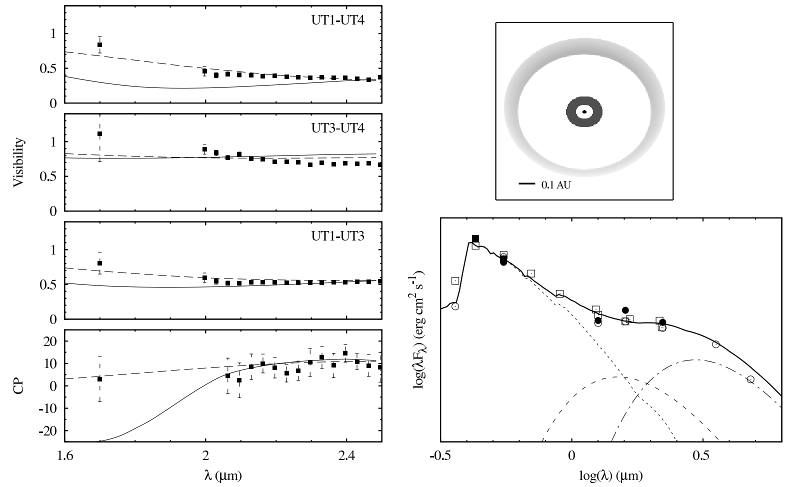

Fig. 4. Left: H and K band visibilities and closure phases of MWC758, from Isella et al. (2008). The solid line represents the model of dust inner rim only, the dashed one being the unresolved point + dust model as shown in the right top corner. Below is shown the SED, well reproduced by the star (dotted line) + unresolved point (dashed line) + dust (dashdotted line) model.

changes slightly the parameters of the dusty rim (T_{sub} = 1300K, R_{in} = 0.40AU). What is then the physical interpretation for this unresolved component? Given the temperature and the size ($\leq$ 0.1AU) of the emission region, it is likely that AMBER is directly probing the hot gas accreting close to to the star. And indeed, models of accreting gas developed by Muzerolle et al. (2004) (assuming an accretion rate of $\sim 2.10^{-7} M_{\odot}/yr$ from the star's Brγ luminosity), allow as well to satisfactory fit the shape of the SED by filling the lack of energy in the H band (see Fig. 4), hence reinforcing this interpretation.

4 Conclusion and perspectives

In summary, AMBER is so far a unique tool – in terms of spectral bands (H,K), together with spectral resolution (R=35,1500,12000) – to probe the internal region of YSO, not only for the dust but also for the gas emissions. Note that from this semester of observation, the FINITO fringe tracker is now available with the 8m telescopes of the VLTI, hence allowing to drastically increase the precision of the measurements, as well as its sensibility that enable to probe fainter emission lines (CO, Fe?,...) and to use the high spectral resolution mode of R=12000 to access the kinematics (velocity maps) of the gas along the lines.

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