SF2A 2006
D. Barret, F. Casoli, T. Contini, G. Lagache, A. Lecavelier, and L. Pagani (eds)

AMBER/VLTI SPECTROSCOPY OF YOUNG STARS : A DISK-WIND AROUND THE HERBIG AE STAR HD104237

E. Tatulli[1], A. Isella[1], A. Natta[1], L. Testi[1], A. Marconi.[1] and the AMBER consortium

Abstract. We investigate the origin of the Brγ emission at the Astronomical Unit (AU) scale in the Herbig Ae star HD104237. Using AMBER/VLTI at a spectral resolution $\mathcal{R} = 1500$ near the Brγ line, we resolve the emission spatially and spectrally. The differential visibility does not show variations between the continuum and the Brγ line, although the line is clearly detected in the uncorrelated spectrum with a peak intensity 35% higher than the continuum. We assume that the continuum excess emission in the K-band is produced in a "puffed-up" inner rim of the circumstellar disk and discuss the implications of our result on the origin of Brγ. We conclude that the emission most likely arises from a compact disk wind, launched from a region 0.2-0.5 AU from the star, with a spatial extension similar to that of the near infrared continuum emission region, i.e, very close to the inner rim location.

1 Introduction

The spectra of pre-main sequence stars of all masses show prominent strong and broad emission lines of both hydrogen and metals. These lines trace the complex circumstellar environment that characterizes this evolutionary phase, and are very likely powered by the associated accretion disks. The emission lines are used to infer the physical properties of the gas, and to constrain its geometry and dynamics. Their exact origin, however, is not known. The hydrogen lines, in particular, may originate either in the gas that accretes onto the star from the disk, as in magnetospheric accretion models (Hartmann et al. 1994), or in winds and jets, driven by the interaction of the accreting disk with a stellar (Shu et al. 1994) or disk (Casse & Ferreira 2000) magnetic field. For both models, emission in the hydrogen lines is predicted to occur over very small spatial scales, a few AUs at most. Therefore, to understand the physical processes that occur at these scales one needs to combine very high spatial resolution with enough spectral resolution to resolve the line profile. AMBER, the three-beam near-IR recombiner of the VLTI (Petrov et al. 2003), simultaneously offers high spatial and high spectral resolution, with the sensitivity required to observe pre-main sequence stars.
We focus here on the Herbig Ae system HD104237. The central emission line star, of spectral type between A4V and A8, is surrounded by a circumstellar disk, which causes the infrared excess emission (Meeus et al. 2001) and drives a jet seen in Ly-α images (Grady et al. 2004). The optical spectrum shows a rather narrow Hα emission with a P-Cygni profile (Feigelson et al. 2003). The disk is seen almost pole-on ($i = 18^{\circ}{}^{+14}_{-11}$; Grady et al. 2004), consistent with the low value of $\mathrm{v} \sin i$ (12 km s^{-1}; Donati et al. 1997). In the near infrared domain, spatially unresolved ISAAC observations (Garcia Lopez et al. 2006) show a strong Brγ emission line, with a peak flux 35% above the continuum.

2 Observation and data reduction

AMBER observed HD104237 on 26 February 2004 on the UT2-UT3 baseline of the VLTI, which corresponds to a projected length of $B = 35$m. The instrument was set up to cover the $[2.121, 2, 211]\mu$m spectral range with a spectral resolution of $\mathcal{R} = 1500$, which resolved the profile of the Brγ emission line at 2.165μm. The Brγ emission is well detected in the temporal average spectrum of the AMBER photometric channels, and it contributes 35% of the total flux (Fig. 1, central panel). For comparison we overlay a higher spectral resolution

[1] Osservatorio Astrofisico di Arcetri

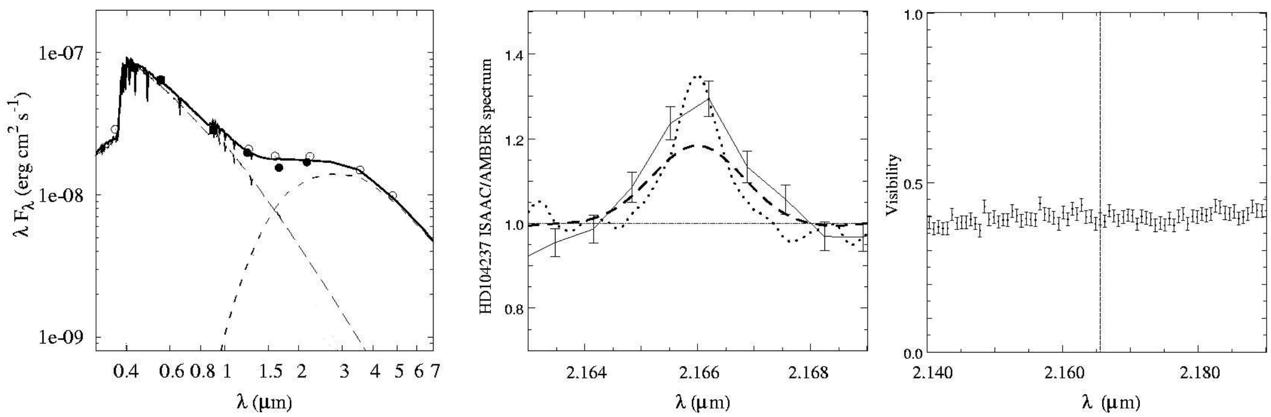

Fig. 1. Left: SED predicted by the "puffed-up" rim model used to normalise the K-band continuum visibility. The contributions of the A star (long-dashed line) and of the rim (short dashed line) are shown. Center: Comparison of Brγ observed with AMBER in the photometric channels (solid line) and ISAAC (dotted line); the dashed line shows the ISAAC spectrum smoothed to the spectral resolution of AMBER. Right: Visibility of HD104237 as a function of wavelength. The continuum has been normalised using the star + rim model, as described in the text. The vertical line shows the Brγ wavelength.

spectrum ($\mathcal{R} = 8900$, taken with ISAAC approximately one year before the VLTI observations), as well as its smoothing to the AMBER spectral resolution.

Data reduction followed standard AMBER procedures (Tatulli et al. 2006). However, for these observations the visibility amplitude could not be calibrated to an absolute scale using an astronomical calibrator (unresolved star), due to non-stationary vibrations in the optical train of the UT telescopes. Fortunately the contrast loss from vibrations is achromatic across our small relative bandpass, and as a consequence the differential visibility, that is, the relative visibility between the spectral channels, is unaffected. Our dataset therefore allows us to investigate the visibility across the Brγ emission line compared to that in the adjacent continuum. The differential visibilities are accurate to approximately 5%.

The excess near infrared continuum emission in Herbig Ae stars most likely originates in the innermost regions of their dusty circumstellar disks, at the dust sublimation radius (Eisner et al. 2005; Isella et al. 2006). To approximately normalise the visibilities, we thus scaled the observed continuum value to the predictions of appropriate theoretical models of the disk inner rim emission (Isella & Natta 2005). We computed the structure of the "puffed-up" inner rim as described in Isella et al. (2006). We used for the star the following parameter: $T_{eff} = 8000K$, $L_\star = 30L_\odot$. We adopted a distance of $D = 115pc$, and a disk mass surface density of $\Sigma(r) = 2 \cdot 10^3 \cdot r^{-3/2}$g/cm^2 (with r in AU).

Fig. 1 (left) shows that the model using micron size astronomical silicates produces a very good fit of the SED. The star fluxes contribute approximately 30% of the total 2.15μm flux, and the inner rim appears as a bright ring with radius $R_{rim} = 0.45$AU (3.8mas at $D = 115pc$). The resulting model visibility on the 35m baseline is $V = 0.38$ (Fig 1, right).

2.1 *Analysis*

Within the fairly small error bars, the visibility does not change across the Brγ emission line. This result is robust and puts strong constraints on the relative spatial extent of the line and continuum emission regions, demonstrating that they have very similar apparent sizes. We use this constraint to probe the processes responsible for the the Brγ emission in this star, and consider in turn the two main mechanisms usually invoked to interpret the hydrogen line emission in pre-main-sequence stars. We translate both mechanisms to simple geometrical models of specific spatial extension, with the line strength fixed at the observational value, and evaluate the resulting visibility across the line. Note that this analysis is valid as long as the continuum

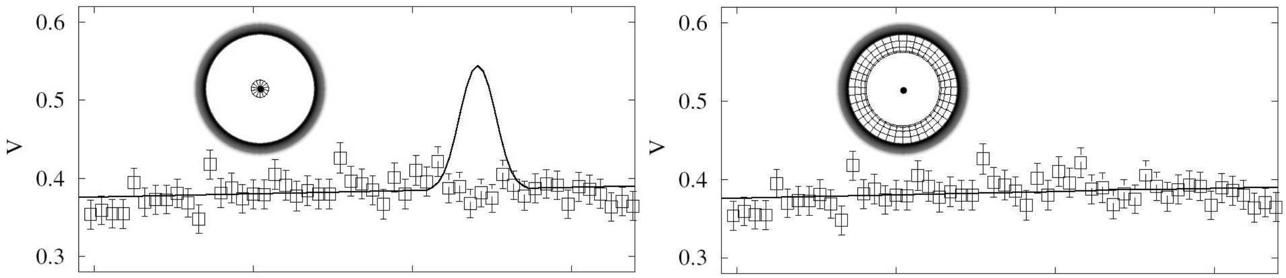

Fig. 2. Comparison between the observed visibilities (empty square with error bars) and the predictions (solid curves) of the simple geometrical models for the Brγ emission (sketched in the same panels). The observed visibilities are scaled to match the continuum value predicted by the "puffed-up" inner rim model as described in Sec.2. The continuum emission arises both from the stellar photosphere ($\approx$30%) and from the dusty disk inner rim, located at the dust evaporation distance $R_{rim} = 0.45$AU and which appears as the bright gray scale ring. The Brγ emission regions are shown as grid surfaces. The left panel represents the *magnetospheric accretion* model in which the Brγ emission originates very close to the star, inside the corotational radius R_{corot} =0.07AU. The right panel shows the *outflowing wind* model, in which the emission is confined close to the inner rim, between $\sim$ 0.2AU and $\sim$ 0.5AU.

emission is *resolved*. In our case the continuum is calibrated by a model and not by an unresolved star, and therefore there might be a chance that the visibility of the continuum is close to 1. However, this peculiar scenario appears very unlikey since the puffed-up rim model has been shown to be well representative of the very close environment of Herbig Ae stars over a large luminosity range (Monnier et al. 2005). Furthermore, the hypothesis of a resolved continuum emission for HD104237 is strongly supported by its measured accretion rate of $10^{-8}M_{\odot}$ (Grady et al. 2004). Indeed, Muzerolle et al. (2004) showed that for weak accretion rates ($\dot{M} < 10^{-7}M_{\odot}$/yr), the gas accreting onto the star is optically thin. It therefore does not shield the dust from the stellar radiation and consequently, the star must exhibit an inner region free of dust, large enough to be resolved by the interferometer at the 35m baseline.

Magnetospheric accretion: in such a model matter infalls on the star along magnetic field lines, and the base of this infalling flow is (approximately) inside the corotation radius (Muzerolle et al. 2004). For HD104237 we find $R_{corot} = 0.07$AU, using $v \sin i = 12$km/s Donati et al. (1997) and an inclination of $i = 18^{\circ}$ (Grady et al. 2004). Adopting R_{star} and R_{corot} as the inner and outer limits of the magnetospheric accreting region, Fig. 2 (left) demonstrates that Brγ emission is then confined much closer to the star than the dusty rim. The predicted visibility therefore increases significantly in the line, contrary to the observational result. Explaining the observed visibility with magnetospheric accretion requires the corotation radius to approach the inner rim, which would need an unrealistically lower stellar rotational velocity (v < 2km/s). The magnetic field of HD104237 is weak, $B = 50G$ (Donati et al. 1997), and the corresponding magnetospheric truncation radius ($R_{mag} = 0.018$AU, Shu et al. (1994)) is smaller than the corotation radius. Replacing R_{corot} by R_{mag} as the outer radius of the magnetospheric accreting region would thus only reinforce our conclusion. Magnetospheric accretion therefore cannot be responsible for most of the Brγ emission.

Outflowing wind: the remaining possibility is that Brγ is emitted in a wind or jet. The bulk of the emission is then confined to the regions of highest gas density, i.e., to the base of the wind/jet. Since the wind/jet must be seen almost pole-on, we assume in our model that emission is confined to a ring of width ΔR, with $\Delta R/R_i \sim 0.5$, where R_i is the ring inner radius, that is the wind launching point. This assumption is guided by the wind models of Natta et al. (1988), and by the more recent simulations of the Paβ emission in jets of T Tauri stars (Thiébaut et al. 2003). For pole-on outflows most of the intensity originates in a ring with these approximate properties. Fixing $\Delta R/R_i = 0.5$ and adjusting R_i, this model reproduces the interferometric data for R_i between $\sim$ 0.25 AU and 0.35 AU (Fig. 2, right panel). Allowing different relative widths (ΔR from 10% to 100% of R_i), we find that the Brγ emission has to originate between $\sim$ 0.2 and 0.5 AU. Our interferometric measurements are therefore consistent with the Brγ emission coming from the base of a wind, originating in a disk region close to the location of the dusty rim. The presence of a wind in HD104237 is well established on (much) larger scales, by the Lyα bipolar microjet (Grady et al. 2004) and by the P-Cygni profile of the Hα line (Feigelson et al. 2003). Given our oversimplified geometrical models, it would be inappropriate to speculate too much on the detailed nature of the wind. We note however that the launching region of an X-wind, driven by the stellar magnetic field (Shu et al. 1994), is close to the corotation radius and too small to be consistent with the present data. Making the X-wind acceptable needs one to relax the assumption that most of the line emission originates near the launching point, and instead have the brightest Brγ region a factor $5-8$ further away from the star. The disk-wind scenario in contrast has its launching point a few tenths of an AU from the star and needs no adjusting. This preference for a disk-wind is consistent with the size of the jet launching regions inferred from the rotation of TTauri jets (Coffey et al. 2004).

3 Conclusions

We have presented interferometric observations of the Herbig Ae star HD104237, obtained with the AMBER/VLTI instrument with $\mathcal{R} = 1500$ high spectral resolution. The visibility is identical in the Brγ line and in the continuum, even though the line represents 35% of the total 2.165μm flux. This implies that the line and continuum emission regions have the same apparent size.
Scaling the continuum visibility with a "puffed-up" inner rim model, and using simple models to describe the Brγ emission, we have shown that the line emission is highly unlikely to originate in magnetospheric accreting columns of gas. On the contrary, it is much more likely to come from a compact outflowing disk wind launched in the vicinity of the rim, about 0.5 AU from the star. This does not preclude accretion from occuring along the stellar magnetic field detected by Donati et al. (1997), and accreting matter might even dominate the optical hydrogen line emission, but our observations show that the bulk of the Brγ emission in HD104237 is unlikely to originate in magnetospheric accreting matter.
Our results show that AMBER/VLTI is a powerful diagnostic of the origin of the line emission in young stellar objects. Observations of a consistent sample of objects will strongly constrain the wind launching mechanism.

References

Casse, F., & Ferreira, J. 2000, A&A, 353, 1115

Coffey, D., Bacciotti, F., Woitas, J., Ray, T. P., & Eislöffel, J. 2004, ApJ, 604, 758

Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., & Collier Cameron, A. 1997, MNRAS, 291, 658

Eisner, J. A., Hillenbrand, L. A., White, R. J., Akeson, R. L., & Sargent, A. I. 2005, ApJ, 623, 952

Feigelson, E. D., Lawson, W. A., & Garmire, G. P. 2003, ApJ, 599, 1207

Grady, C. A., et al. 2004, ApJ, 608, 809

Hartmann, L., Hewett, R., & Calvet, N. 1994, ApJ, 426, 669

Isella, A., & Natta, A. 2005, A&A, 438, 899

Isella, A., Testi, L., & Natta, A. 2006, to appear in A&A, (astro-ph/0601438)

Meeus, G., Waters, L. B. F. M., Bouwman, J., van den Ancker, M. E., Waelkens, C., & Malfait, K. 2001, A&A, 365, 476

Monnier, J. D., et al. 2005, ApJ, 624, 832

Muzerolle, J., D'Alessio, P., Calvet, N., & Hartmann, L. 2004, ApJ, 617, 406

Natta, A., Giovanardi, C., & Palla, F. 1988, ApJ, 332, 921

Petrov, R. G., et al. 2003, SPIE, 4838, 924

Shu, F., Najita, J., Ostriker, E., Wilkin, F., Ruden, S., & Lizano, S. 1994, ApJ, 429, 781

Tatulli, E., et al. 2006, to appear in A&A, (astro-ph/0602346)

Thiébaut, E., Garcia, P. J. V., & Foy, R. 2003, Ap&SS, 286, 171