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AMBER **high-spectral resolution interferometry of Be stars: More than just stars and disks?**

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Abstract. High spectral-resolution Br γ VLTI/AMBER observations of classical Be stars reveal complex visibility, phase, and closure phase profiles, which were not seen in previous lower-resolution data. They present new challenges for the modeling of Be stars and may require additional ingredients over and above the conventional central star + circumstellar disk paradigm.

1. Motivation and targets

AMBER (Petrov et al. 2007) was the first high-spectral resolution (HR, R = 12 000) interferometric instrument and still is the only one capable of taking closure phase data in this mode. After the commissioning in the end of 2008, the spectral resolution was increased eightfold wrt. its medium-resolution mode, and it is about 30 times as high as that of CHARA/MIRC (Monnier et al. 2004). The present (2011) list of standard HR settings comprises 14 central wavelengths but most of the actual HR observations cover the Br γ spectral region.

The order-of-magnitude increase in spectral resolution entails the potential for a qualitative leap forward in studies of objects with a considerable range in dynamics in general and rotationally supported disks of young or evolved stars in particular, which account for a large fraction of all available VLTI observations.

In order to explore this potential for classical Be stars, we have combined data from three AMBER projects of our own with selected archival observations. The objects in Tab. 1 include almost all Be stars observed to date with AMBER in its HR mode. Only Achernar (α Eri) was not included because it had but a tiny disk at the time of the AMBER observations. Observations were done both with the 8.2m diameter Unit Telescopes (UTs) and the 1.8m Auxiliary Telescopes (ATs). Because even the

largest circumstellar Be disk diameters in Br γ are of a few miliarcseconds, the longest baselines – UT1-UT3-UT4 or UT1-UT2-UT4 triplets, D0-H0-G1-I1 or A0-K0-G1-I1 ATs quadruplets – were used for observations. All data were reduced with the help of the yorick amdlib3 reduction package (Tatulli et al. 2007; Chelli et al. 2009).

Table 1.   Classical Be stars observed in AMBER HR mode and Br γ region in 2008-2010. Parameters of the targets are taken from the Simbad database.

| Star	HD	Spectral type	v sin i [km/s]	K_{mag} [mag]	parallax [mas]	Epoch
ζ Tau	37202	B2IV	310	2.81	7.82	Oct 15, 2008
α Col	37795	B7IVe	195	2.83	12.16	Jan 9,10, 20, 2010
κ CMa	50013	B1.5IVe	210	3.55	4.13	Jan 9, 10, 17, 2010
ω CMa	56139	B2IV-Ve	105	4.37	3.53	2008-2010, large dataset
β CMi	58715	B8Ve	210	3.10	19.16	Dec 31, 2009
ω Car	89080	B8IIIe	220	3.45	8.81	Dec 21, 2008
48 Lib	142983	B5IIIp(?)	395	4.59	6.36	May 12, 2009
δ Sco	143275	B0.2IVe	165	2.43	8.12	2009-2011; continuing obs.
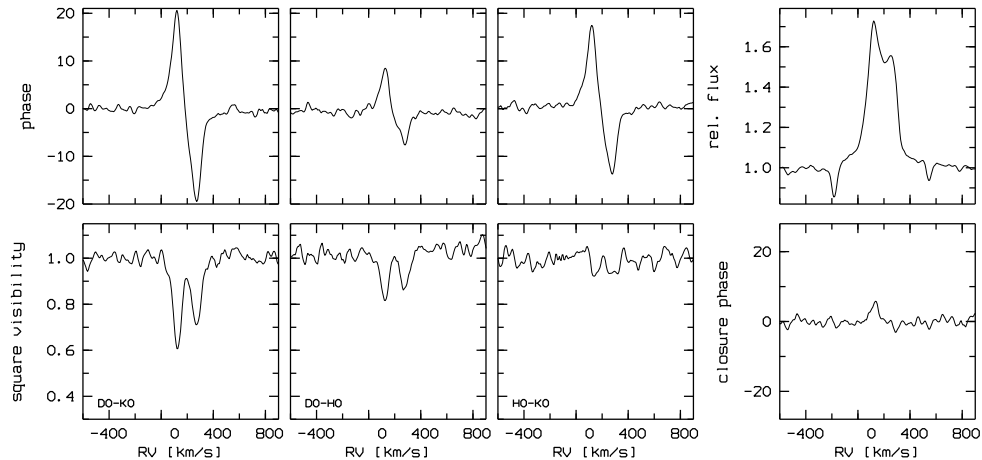
Figure 1. κ CMa observed on January 9, 2010, AT baseline configuration D0-H0-K0. The baseline lengths and position angles are: D0-H0 64.0m@71.0°, H0-K0 32.0m@71.0° and D0-K0 96.0m@71.0°. Although canonical S-shaped profiles appear in phase diagrams, a double-peak reversal can be seen in all visibilities.

2.   Results

The generally expected – and at low and medium spectral resolution often confirmed – scheme of the interferometric appearance of circumstellar disks results from simple uniform or Gaussian disk models and consists of a single central reversal (akin to a

spectral flux profile with a stellar absorption line) in the visibility and a smooth S-shaped phase profile. The canonical phase profile as exhibited by κ CMa is shown in Fig. 1.

By contrast, HR AMBER observations of Br-γ square visibilities, phases, spectroscopic normalized fluxes, and closure phases in all Be stars in Tab. 1 reveal much more complex structure (Figs. 1, 2 and 3). Broadened, double- or multiple-peak profiles commonly appear in the visibilities. In phase, a third peak is sometimes seen superimposed to the center of the expected S-shaped profile. In some cases, this phase reversal merely is a small perturbation of the S-shaped profile, but in others it reaches an amplitude comparable to the one of the main peaks. Both visibility and phase profiles are very strongly dependent on the projected position angle of the baseline used for the observations. Similar patterns are not known from interferometry of targets other than Be stars and so are asking for a special interpretative effort.
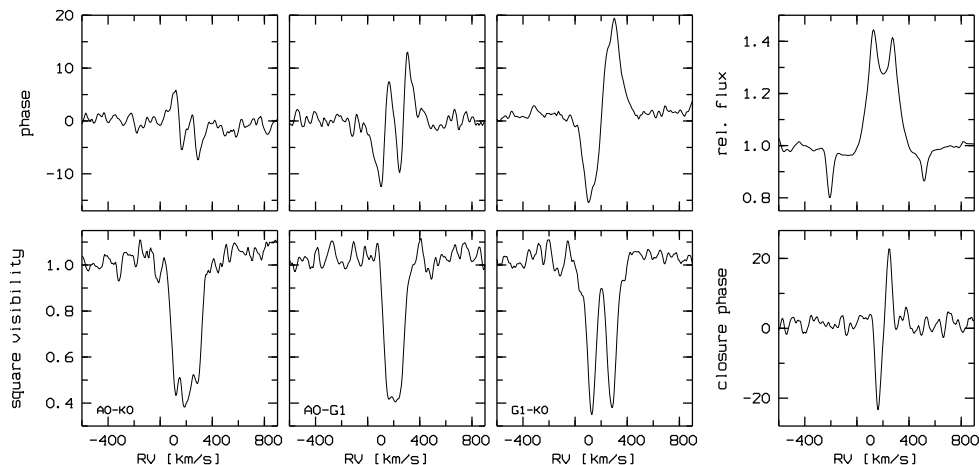

Figure 2. α Col observed on January 20, 2010 (HJD 55216.083), AT telescopes at the baseline configuration A0-K0-G1. The baseline lengths and position angles are: A0-K0 128.0m@71.0°, K0-G1 90.5m@26.0° and A0-G1 90.5m@116.0°.

The following is an attempt to briefly describe the most prominent features in the visibility and phase profiles of the stars in the sample. Remember that their appearance is strongly dependent on the projected position angle of the baseline.

ζ **Tau:** The only HR observation was obtained during the AMBER HR science verification run in October 2008 and is of relatively low quality. An asymmetric double peak visibility profile emerges at all baselines. A sharp peak of different height is superimposed to a shallow S-shape phase profile.

α **Col:** Visibilities possess a double- or multi-peak structure, and phases show a strong reversal at two baselines. The closure phase indicates a very strong disk asymmetry, see Fig. 2.

κ **CMa:** A double-peak structure in the visibility is seen even at shorter baselines, S-shaped phase profiles at all baselines.
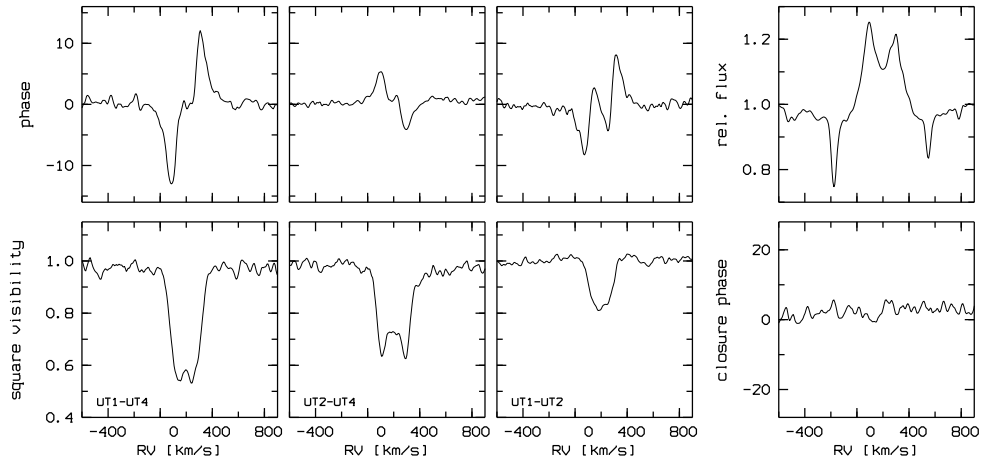
Figure 3. β CMi observed on December 31, 2009 (HJD 55196.190), baseline con-
figuration UT1-UT2-UT4. The baseline lengths and position angles are: UT1-UT2
56.6m@26.2°, UT2-UT4 89.4m@81.3° and UT1-UT4 130.2m@60.4°.

β **CMi:** A phase reversal and a double/multiple visibility structure appear at all base-
lines for this very nearby Be star although the closure phase only suggests a
negligible disk asymmetry, see Fig. 3.

28 (ω) CMa: A pole-on view of the star is offered from H α emission line profiles and
was also confirmed by modeling of rapid variations of photospheric lines due to
non-radial pulsation. Maintz et al. (2003) derived the inclination of the rotational
axis $i = 15°$ or $24°$. Double-peak visibility profiles in 28 CMa show that the
feature can appear even in stars with supposedly little line-of-sight motions in the
disk. At some epochs, a weak phase reversal is present at the G1-K0 baseline, but
pure S-shaped profiles result from observations at the other baselines. Analysis of
a large dataset obtained in 2009-2010 is in progress (Štefl et al., in preparation).

48 Lib: The huge almost over-resolved disk shows strong double-peak visibility and
closure phase profiles, a strong phase reversal appears at one baseline. For a
more detailed discussion see Štefl et al. (A&A, to be submitted).

δ **Sco:** Phase reversal and double-peak visibility profiles dominate at some baselines.
A comprehensive analysis of all data is in progress (Štefl et al., in preparation).

The key role of the high spectral resolution for interferometry of Be stars is demon-
strated in a simple way in Fig. 4. The double peak visibility at the A0-G1 baseline and
phase profile at the A0-K0 baseline, showing a strong phase reversal, are rebinned to
the AMBER medium and CHARA/MIRC highest resolution. The fine structure both in
visibility and phase is lost already in the AMBER medium resolution and these char-
acteristics appear as single reversals of reduced amplitude. Its position at the MIRC
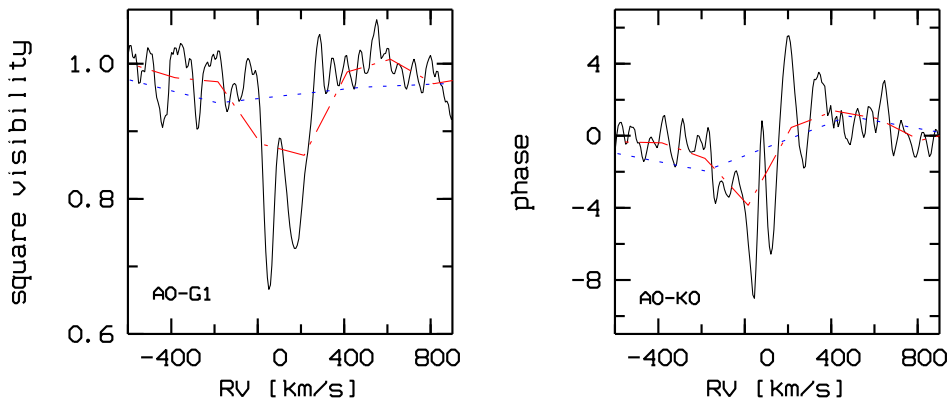resolution is moreover biased by the starting wavelength of the wavelength/RV grid.

Figure 4.   The effect of the spectral resolution demonstrated on observations of δ Sco obtained on May 10, 2010. Visibility at the A0-G1 baseline and phases at A0-K0 are shown. The full black line represents AMBER HR observations, which are rebinned to AMBER medium resolution of R=1500 (overplotted as the dashed red line) and the highest MIRC resolution R=450 (dotted blue line).

3.   Summary and conclusions

The AMBER HR database of classical Be stars documents that both double/multiple visibility profiles and phase reversals are common features. Double/multiple-peak visibility profiles appeared in all observed Be stars at some baseline(s) and time(s). Their occurrence and peak separation do not seem to depend on the length of the baseline. Asymmetric visibility profiles may correspond to a transition between single and double peak profiles. Because not even in the most nearby objects in our sample the central stars are resolved, the double-peak visibility profiles are not caused by the superposition of stellar and disk visibilities.

Phase reversals occurred in five of the eight observed Be stars: (ζ Tau, α Col, β CMi, 48 Lib, δ Sco, and ω CMa). The preferential detection of phase reversals at long baselines may locate the responsible physical process close to the star. In β CMi, the feature is strong also at the 45m UT1-UT2 baseline; however, this is a very nearby star.

Two of the stars showing a phase reversal are Be shell stars seen equator-on (ζ Tau, 48 Lib). However, the limited database (only one HR observation for 4 targets, 3 observations of different quality for 2 targets) does not permit phase reversals and visibilities with more than one peak to be linked to disk position angle. For 28 CMa and δ Sco this point will be discussed in dedicated papers. Nevertheless, the small sample indicates that these features occur over a broad range of spectral B sub-types and disk viewing angles, from equator-on to at least medium inclination. Their presence in steady-state phases of the disks around three stars (α Col, β CMi, κ CMa) and also shortly after an outburst in ω CMa suggests that the observed phase reversals are unrelated to a special disk evolution phase.

The implied commonality in Be star disks of multiple-peak visibility profiles and phase reversals represents a major challenge for disk models. They do not match the S-shaped disk phase profiles, which are observed at lower spectral resolution and form

the basis of commonly accepted models. Without quantitative modeling, their interpretation is rather speculative.

Our preliminary efforts (Carciofi et al., in preparation) suggest that secondary dynamical disk effects may explain double-peak visibility profiles and phase reversals at baselines perpendicular to the assumed equatorial plane (48 Lib, δ Sco). This is crudely consistent with the observed position angle-dependence in some stars. However, the model is struggling with phase reversals at baselines parallel to the equatorial plane (as in α Col or β CMi). Therefore, an alternative view is developed in Rivinius et al. (A&A, to be submitted). With polar mass outflows, it goes beyond the canonical central star + circumstellar disk paradigm for classical Be stars but may not be applicable to all classical Be stars.

Obviously, high spectral resolution adds a new and essential dimension to interferometry of objects with significant internal motions. This is demonstrated by the here presented observations of classical Be stars.

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