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Ellerbroek, L.E.

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A resolved, AU-scale gas disk around the B[e] star HD 50138


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Abstract

HD 50138 is a B[e] star surrounded by a large amount of circumstellar gas and dust. Its spectrum shows characteristics which may indicate either a pre- or a post-main-sequence system. Mapping the kinematics of the gas in the inner few AU of the system contributes to a better understanding of its physical nature. We present the first high-resolution spectro-interferometric observations of the Brγ line, obtained with VLTI/AMBER. The line emission originates from a region more compact (up to 3 AU) than the continuum-emitting region. Blue- and red-shifted emission originates from the two different hemispheres of an elongated structure perpendicular to the polarization angle. The velocity of the emitting medium decreases radially. We compare the data with a geometric model of a thin Keplerian disk and a spherical halo. Most of the data are well reproduced by this model. The evolutionary state of the system is discussed; it is most likely a binary system evolved just off the main sequence surrounded by a gaseous inner disk and a dusty outer disk.
7.1 Introduction

B[e] stars are an enigmatic class of stellar objects, the nature of which is in many cases unknown and strongly debated. They are defined as stars with spectral type B which show forbidden emission lines in their optical spectra, as well as a strong near-infrared excess (Slettebak 1976; Allen & Swings 1976; Zickgraf 1998). The forbidden lines originate in a tenuous circumstellar medium, while a dust envelope or disk radiates in the infrared. The denomination “B[e] star” is phenomenological; the defining characteristics can be produced by a heterogeneous set of astrophysical objects. Among its members are both young (pre-main-sequence stars) and evolved systems (e.g., supergiants, interacting binaries, and planetary nebulae). For many systems, determining their configuration and evolutionary state proves to be a difficult observational challenge (Lamers et al. 1998; Miroshnichenko 2007).

Lamers et al. (1998) formulated a classification scheme for B[e] stars of different nature based on their spectral lines, luminosity and environment. For some objects, however, the diagnostics in Lamers’ scheme are inconclusive. These systems may be better understood by combining observations with high resolution in the spectral, spatial and temporal domain. In the last decade, a new generation of high-resolution near-infrared interferometers have become available. With these, circumstellar gas dynamics can be mapped with unprecedented spatial (micro-arcsecond) and spectral ($\Delta v \sim 20 \text{ km s}^{-1}$) resolution. This has been a successful method to resolve some of the most intensely debated B[e] systems (Domiciano de Souza et al. 2007; Millour et al. 2009; Kraus et al. 2012; Wang et al. 2012; Wheelwright et al. 2012a,b, 2013). In most of these cases, binary interaction is the most probable cause of the complex circumstellar environment. Gas disks are found to dominate the emission in the inner few AU; only in a few cases a Keplerian velocity field can be resolved (e.g., Kraus et al. 2012).

In this Chapter, we present the first high-resolution spectro-interferometric study of the puzzling B[e] star HD 50138 (V743 Mon, MWC 158). Being among the brightest B[e] stars in the sky, it is located at a distance of $500 \pm 150$ pc (van Leeuwen 2007) and has not been associated with a star-forming region. It may be part of the Orion-Monoceros molecular cloud complex (Maddalena et al. 1986), but because of the uncertainty in the distance, this cannot be confirmed.

Despite the ample amount of observations and literature, no definitive conclusion has been put forward regarding its evolutionary state. Arguments have been made to classify it as a pre-main-sequence object (Morrison & Beaver 1995) or a star on, or just evolving off the main-sequence (Borges Fernandes et al. 2009, BF09). For more discussion on its evolutionary state, see e.g., Jaschek et al. (1993); Jaschek & Andrillat (1998); Lamers et al. (1998). The main property favoring a pre-main-sequence nature are spectral infall signatures. Conversely, the isolation of the object and the occurrence of shell phases have been interpreted as signs of a post-main-sequence nature. Many characteristics are ambiguous, like the large infrared excess and the possible binarity of the source (Cidale et al. 2001; Baines et al. 2006). An examination of the gas kinematics close to the source, and a constraint on the possible binarity of the system may lead to
an improved understanding of the evolutionary state.

The circumstellar dust around the system is distributed in an aspherical geometry, well represented by a moderately inclined disk, \( i = 56 \pm 4^\circ \), as determined by Borges Fernandes et al. (2011, BF11) based on near- (AU-scale) and mid-infrared (10 AU-scale) interferometry. The same authors find an orientation of the disk major axis, \( \psi = 71 \pm 7^\circ \), perpendicular to the polarization angle \( (159 \pm 4^\circ) \), Bjorkman et al. 1998; Yudin & Evans 1998; Oudmaijer & Drew 1999). Signatures of outflowing and infalling gas are found in emission lines (Morrison & Beaver 1995; Grady et al. 1996; Pogodin 1997; BF09; Borges Fernandes et al. 2012, BF12). Spectropolarimetry by Bjorkman et al. (1998) suggests that a geometrically thin gas disk exists, where electron scattering dominates the polarization. Other polarimetry studies also find evidence for a circumstellar rotating disk or equatorial outflow (Oudmaijer & Drew 1999; Harrington & Kuhn 2007, 2009).

Spectro-astrometry by Baines et al. (2006) shows a shift of the photocenter and a decreasing spatial width across the H\( \alpha \) line. This is interpreted by the authors as being a sign of a binary companion on an orbit of order 50 – 100 AU (R. Oudmaijer, private communication). The circumstellar material may be the result of the interaction with a much closer companion. Given the limited time sampling of monitoring campaigns to date, no evidence for a spectroscopic binary has been found (Corporon & Lagrange 1999; BF12). Photometric and spectroscopic variability is detected on timescales from days to years from as early as the 1930s. This has been attributed to shell phases and outbursts, during which the ejected material absorbs and scatters radiation in lines and in the continuum. This remains an actively discussed phenomenon (Merrill 1931; Merrill & Burwell 1933; Doazan 1965; Hutsemékers 1985; Andrillat & Houziaux 1991; Halbedel 1991; Bopp 1993; Pogodin 1997, BF09, BF12).

In this Chapter, we put some of the hypotheses for the dynamics of the circumstellar gas around HD 50138 to the test. We focus on the kinematics of the Br\( \gamma \) emission line. We present a series of observations performed with the *Astronomical Multi-Beam Combiner* (AMBER) on the *Very Large Telescope Interferometer* (VLTI) and with VLT/X-shooter, both located on Cerro Paranal, Chile. The observations are described in Sect. 7.2. We present the optical-to-infrared stellar and circumstellar spectra in Sect. 7.3. In Sect. 7.4, we present the most important trends and signatures found in the AMBER Br\( \gamma \) data. With baselines up to 120 m and a high spectral resolution (up to \( v = 20 \text{ km s}^{-1} \)), we are able to resolve micro-arcsecond structures in the line emission. In Sect. 7.5, the interferometric observations are compared to a geometric model, which consists of a Keplerian disk and halo. We discuss the validity of this and other possible model geometries in Sect. 7.6. The implications for the object’s evolutionary state are also considered. The main conclusions of this work are presented in Sect. 7.7.
A RESOLVED, AU-SCALE GAS DISK AROUND THE B[e] STAR HD 50138

Figure 7.1: Coverage of the ($u$, $v$)-plane of the AMBER-observations with $\mathcal{R} \sim 12,000$ (filled symbols) and $\mathcal{R} \sim 1500$ (open symbols). The dashed line is aligned with the major axis of the modeled disk ellipse ($\psi = 71^\circ$). Colors indicate the baseline PA with respect to this line.

Table 7.1: Journal of the AMBER interferometric observations.

<table>
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<th>No.</th>
<th>Date</th>
<th>Configuration</th>
<th>$B$ (m)</th>
<th>PA (°)</th>
<th>$\mathcal{R}$</th>
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<td>15 / 29 / 44</td>
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<td>12000</td>
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<tr>
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<td>13 / 26 / 38</td>
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<td>12000</td>
</tr>
<tr>
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<td>U2U3U4</td>
<td>43 / 62 / 86</td>
<td>37 / 108 / 80</td>
<td>12000</td>
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<tr>
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<td>U2U3U4</td>
<td>45 / 58 / 86</td>
<td>45 / 114 / 84</td>
<td>12000</td>
</tr>
<tr>
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<td>U2U3U4</td>
<td>46 / 61 / 89</td>
<td>43 / 111 / 83</td>
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<td>1500</td>
</tr>
<tr>
<td>8</td>
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<tr>
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<td>G1D0(H0)</td>
<td>54 / 48 / 71</td>
<td>161 (73 / 24)</td>
<td>1500</td>
</tr>
</tbody>
</table>

7.2 Observations and data reduction

7.2.1 Spectroscopy: VLT/X-shooter

Spectra of HD 50138 were obtained on 2013-02-14, UT 04:53, with X-shooter on the VLT. X-shooter covers the optical to near-infrared spectral region in three separate arms: UVB (290–590 nm), VIS (550–1010 nm) and NIR (1000-2480 nm; Vernet et al. 2011). Narrow slits were used: 0.5″, 0.4″ and 0.4″ in the three spectrograph arms, respectively. This resulted in a spectral resolving power $\mathcal{R} \equiv \lambda / \Delta \lambda$ of 9100 in UVB, 17,400 in VIS and 11,300 in NIR. The signal-to-noise ratio (S/N) was 120 at 450 nm and 55 at 2150 nm.

The frames were reduced using the X-shooter pipeline (version 1.5.0, Modigliani et al. 2010), employing the standard steps of data reduction, i.e. order extraction,
flat fielding, wavelength calibration and sky subtraction. The wavelength calibration was verified by fitting selected OH lines in the sky spectrum. Flux-calibration was performed using spectra of the spectrophotometric standard star GD153 (a DA white dwarf). The slitlosses were estimated from measuring the seeing full width at half maximum (FWHM, \( \sim 0.9'' \) in \( V \)) from the spatial profile of the point source on the frame. These estimates were refined by comparing the obtained spectral energy distribution (SED) to the averaged photometry (Sitko et al. 2004, see Sect. 7.3.3). This procedure introduces an uncertainty of about 10% in the absolute flux calibration; the relative flux calibration is accurate to within 3%.

The wavelengths and velocities used throughout this Chapter are expressed in the systemic rest frame, for which we adopt 35 km s\(^{-1}\) with respect to the Local Standard of Rest (BF09).

### 7.2.2 Interferometry: VLTI/AMBER

We observed HD 50138 between January 2009 and March 2010, during ten nights. We used the near-infrared instrument AMBER on the VLTI (Schöller 2007). AMBER enables the simultaneous combination of three beams in the \( H \) (1.69-1.73 \( \mu \)m) and \( K \) bands (2.0-2.4 \( \mu \)m), with a spectral resolving power up to \( R \sim 12,000 \) (Petrov et al. 2007).

In an interferometer, two (or more) light beams are combined to form an interference pattern (consisting of “fringes”). The observations are obtained at a spatial resolution \( \lambda/B \), where \( B \) is the baseline separating the telescopes. Two interferometric observables which will be discussed throughout this Chapter, merit some introduction:

- **Visibility** \((V)\): this is the normalized power of the fringes. It quantifies the spatial coherence of a source given a specific baseline, and is thus related to the apparent size of the object; see Sect. 7.4.1.

- **Differential phase** \((\Delta \phi)\): this is the phase offset of the fringes relative to a reference wavelength (in our case, a wavelength where only continuum emission is detected). It probes chromatic shifts of the photocenter projected on the baseline; see Sect 7.4.2.

When discussing the data, we usually refer to the *squared* visibility \( V^2 \), as this is the quantity which is actually measured.

Five measurements have been obtained at medium spectral resolution (\( R \sim 1500, \Delta v \sim 200 \) km s\(^{-1}\)) and five at high resolution (\( R \sim 12,000, \Delta v \sim 25 \) km s\(^{-1}\)). We performed these observations using the relocatable 1.8 m auxiliary telescopes (ATs) and the unit telescopes (UTs), both arrays in two different configurations. The longest baseline is \( \sim 121 \) m, corresponding to a maximum angular resolution \( \lambda/2B \) of 1.8 mas. Figure 7.1 displays the \((u, v)\)-plane coverage of the observations. The position angles (PA) of the baselines are color-coded in this image.

A summary of the observations presented in this Chapter is given in Table 7.1. Each measurement for HD50138 was followed and/or preceded by observations of calibrator targets to measure the instrumental transfer function and to correct for
instrumental effects. All the observations were performed using the fringe-tracker FINITO (Le Bouquin et al. 2008).

The data reduction was performed following standard procedures described in Tatulli et al. (2007c) and Chelli et al. (2009), using the amdlib package, release 3.0.6, and the yorick interface provided by the Jean-Marie Mariotti Center (JMMC) 1. Raw spectral visibilities, differential phases, and closure phases were extracted for all the frames of each observing file. Consecutive observations were merged to enhance the S/N and a selection of 80% of the highest quality frames was made. The transfer function was obtained by averaging the calibrator measurements, after correcting for their intrinsic diameters.

The absolute value of the visibilities obtained with the UT baselines could not be determined because of random vibrations of the telescopes. However, this issue affects all spectral channels in the same way, and does not modify our conclusions. The calibrated data in the OI-FITS format (Pauls et al. 2005) will be included in the JMMC database.

7.2.3 Supplementary data

Additional spectroscopic and photometric data from previous studies and data archives are used in this Chapter. An optical high-resolution ($R \sim 80,000$) spectrum was taken in March 2007 with the Narval spectropolarimeter at the telescope Bernard Lyot at the observatory of Pic du Midi, France. This spectrum was also presented in BF09.

Mid-infrared spectra were obtained on 1999-12-24 and 2003-01-08 with The Aerospace Corporation’s Broad-band Array Spectrograph System (BASS) at the Infrared Telescope Facility (Sitko et al. 2004). This instrument covers the 3–13 $\mu$m wavelength region. BASS is described more fully in Sitko et al. (2008). Magnitudes from the IRAS observatory are also used.

7.3 Results: spectroscopy

In this section, we give an overview of the spectrum of HD 50138. We present spectra obtained with VLT/X-shooter as described in Sect. 7.2.1 and the AMBER Br$\gamma$ spectra. We compare these to the Narval high-resolution optical spectrum obtained in 2007. In Sect. 7.3.1 we constrain the spectral type of the star. Sect. 7.3.2 provides an overview of the gas emission lines and their variability. In Sect. 7.3.3 the distribution of the circumstellar dust is described through the SED.

7.3.1 Spectral type

The spectral type of HD 50138 is difficult to constrain because of the temporal variability. Types in the range B5-A0 and luminosity classes I-V have been proposed in the literature; see references in BF09. The latter authors determine a spectral type of B6-B7 III-V upon

1http://www.jmmc.fr
7.3 Results: spectroscopy

Figure 7.2: Spectra of the He I λ447.1 nm (left) and He (right) lines, obtained with X-shooter (black line) and Narval (gray line). FASTWIND model profiles are overplotted for B6 and B7 giants and main-sequence stars. The inset in the right panel shows a detail of the line wing. The B7 III model provides the best fit with the observed profiles.

For mid- to late-B type spectra, the main temperature diagnostic is provided by the He I λ447 nm line, while the luminosity class is determined from the wings of the He line. Model profiles for these two lines are calculated for the subtypes B6-B7 III-V, using the non-LTE radiative transfer code FASTWIND (Puls et al. 2005). These are compared to the observed profiles in Fig. 7.2; the B7 III model has the best overall fit. An additional temperature diagnostic is provided by the Mg II λ448 nm/He I λ447 nm ratio. The observed ratio exceeds unity, which is the case for types later than B7 (Gray & Corbally 2009). This is one example of the ambiguity of the spectral classification, a possible result of binarity (see Sect. 7.6.1).

7.3.2 Circumstellar gas

The circumstellar gas environment produces many emission lines; nearly 300 are detected in the X-shooter range. A selection representative of the different line morphologies seen across the X-shooter range is displayed in Fig. 7.3. Additional spectra are also plotted to illustrate variability; these are the AMBER spectra of Brγ (R = 12,000), and the Narval optical spectrum. The resolution of the latter spectrum is degraded to match the X-shooter spectrum.

All profiles for which multiple observations are available show some degree of variability. The Hα profile is double-peaked; the red-shifted peak is strongest. The blue-to-red peak intensity ratio is documented to vary between 0.3 and 0.9 (see BF09 and references therein). The other H I profiles also show double peaks; their blue-to-red
Figure 7.3: Selection of spectral lines of HD 50138 obtained with X-shooter, Narval (BF09), and AMBER. All lines show some degree of variability. Note the varying strength of double peaks and the component at $v \sim 0$ km s$^{-1}$. The Narval spectrum is rebinned to match the X-shooter resolution.
variability is not correlated with the Hα variability. The higher Paschen and Brackett transitions have relatively shallow profiles with pronounced peaks. The double peaks in the lower transitions, like Hα and Paδ, are less pronounced and seem to be filled in by an additional broad ($\Delta v \sim 60$ km s$^{-1}$) and sharply peaked component at zero velocity. This is also seen in Brγ, where the profile changes from double- to single-peaked between the different AMBER and X-shooter observations. An abrupt change from single- to double-peaked is also seen in the O I λ844 nm line.

The Fe II lines have broad emission, as well as a narrow, variable absorption component close to zero velocity, which has been attributed to cold material in, e.g., a circumstellar shell or halo (see e.g. Pogodin 1997, BF09). In the high-resolution data, it can be seen that the absorption is a blend of multiple narrow components (BF09). The He I lines (as well as optical Mg II and Si II lines, that are not shown) have a central absorption blended with blueshifted emission around $-100$ km s$^{-1}$. This could be an absorption profile combined with emission in a wind or outflow approaching the observer. It has also been interpreted as an inverse P-Cygni profile indicative of infall (Morrison & Beaver 1995; Pogodin 1997). Which of these two interpretations is correct depends on the value of the systemic velocity; with the adopted value from BF09 the first interpretation (photosphere plus outflow) is favored.
7.3.3 Circumstellar dust

The SED displayed in Fig. 7.4 is compiled from the X-shooter spectrum and infrared data from Sitko et al. (2004). A 13000 K, log $g = 3.5$ atmospheric model (consistent with a B7 III spectral type Kurucz 1993) is overplotted, reddened with an $A_V = 0.4, R_V = 3.1$ extinction law (Cardelli et al. 1989) and scaled to the observed SED. The resulting stellar radius and luminosity are $R_* = 7.0 \pm 2.1 \, R_\odot$ and $L_* = (1.2 \pm 0.4) \times 10^3 \, L_\odot$. The stellar-to-total flux ratio $f = F_*/F_{tot}$ in the $K$-band provides an important constraint for the analysis of the interferometric data (see Sect. 7.4). From the SED fit, we obtain $f = 0.08 \pm 0.01$.

A significant excess emission is present from 1 $\mu$m onwards, amounting to 5.9 mag at 7 $\mu$m. From $\sim 20$ $\mu$m the SED drops as $\lambda F_\lambda \propto \lambda^{-3}$. The steep disk slope is described by a low 30 $\mu$m to 13.5 $\mu$m flux ratio, $[30/13.5] = 0.78 \pm 0.04$ (Acke et al. 2010). The shape of the SED indicates that large amounts of 300 – 800 K dust are present in the inner disk. The circumstellar dust properties are discussed in Sect. 7.6.2.

7.4 Results: AMBER interferometry

In this section we give an overview of the interferometric data from AMBER, which are displayed in Fig. 7.9. The top panel contains the high-resolution observations ($R \sim 12,000, \Delta v \sim 25 \, \text{km s}^{-1}$); the bottom panel the medium-resolution observations ($R \sim 1500, \Delta v \sim 200 \, \text{km s}^{-1}$). An overview is given of the normalized spectrum, squared visibilities, $V^2$, differential phases, $\Delta \phi$, and closure phases, $CP$, of every triplet of baselines. The data are plotted on a velocity scale, where $v = 0$ corresponds to the center of the Br$\gamma$ line, determined from the spectrum by a single Gaussian fit. The error bars correspond to the root-mean-square variability in the continuum region at $500 < |v| < 1000 \, \text{km s}^{-1}$.

Two things are immediately apparent from the shape of the observed profiles. Firstly, the visibility is higher in the line than in the continuum for all baselines. This indicates that at the probed spatial scales, the Br$\gamma$ emitting region is more compact than the region producing the continuum emission. Secondly, in most baselines the differential phase exhibits a “wiggle” across the Br$\gamma$ line. This indicates that the blue-shifted part of the line originates from a different location than the red-shifted part of the line.

We will now approach the interferometric data in a quantitative manner. Essentially model-independent interpretations are given concerning the spatial sizes (Sect. 7.4.1) and photocenter shifts across the line (Sect. 7.4.2).
7.4 RESULTS: AMBER INTERFEROMETRY

7.4.1 Characteristic sizes

The visibility is a proxy for the apparent size of an object. It can be interpreted as the fraction of the total flux that is coherent at an angular resolution set by $\lambda/B$. For a given baseline, a higher visibility implies a more compact object. The translation from visibilities to angular sizes requires their absolute calibration. For short-baseline ($B < 50$ m) observations carried out on the auxiliary telescopes, the effects of random vibrations are reduced and the absolute visibilities are reasonably well calibrated. This was confirmed by comparing our results to $H$-band measurements made with VLTI/PIONIER, whose design allows for an improved visibility calibration compared to AMBER (J. Kluska, private communication).

The analysis of these data is complicated because the observed emission originates from different regions. In this section, we derive the characteristic sizes of the system's components from the absolute visibilities. We consider the three observations in the E0G0H0 configuration (1, 2 and 7, Table 7.1). These baselines are the shortest available, and are all aligned along PA = 72 − 74° (which coincides with the disk major axis found by BF11). The visibilities and angular sizes in this section only refer to this dimension.

We first describe the method by which we disentangle the different components in the data (a similar approach is used in e.g., Weigelt et al. 2007; Eisner et al. 2010; Garcia et al. 2013). We assume that the brightness distribution of the source in the spectral window of interest ($2159 < \lambda < 2173$ nm, $|v| < 1000$ km s$^{-1}$) is made up of three sources:

(i) continuum emission from the star, denoted by subscript “∗”;

(ii) continuum emission from the circumstellar material, “cs”;

(iii) line emission from the circumstellar gas, “line”.

We assume that the photospheric profile is veiled by the circumstellar continuum, so that the first two components are constant across the spectral range. The line emission is wavelength-dependent.

Within the line-emitting part of the spectrum, the observed visibility, $V$, and observed differential phase, $\Delta \phi = \phi - \phi_{\text{cont}}$, are related to these three separate components as

$$ V e^{i \Delta \phi} = \frac{V_{\text{line}} e^{i \Delta \phi_{\text{line}}}}{F_\ast + F_{\text{cs}} + F_{\text{line}}}, $$ (7.1)

where $V_{\text{line}}$ is the line visibility and $\Delta \phi_{\text{line}} = \phi_{\text{line}} - \phi_{\text{cont}}$ is the line differential phase. In the continuum (where $F_{\text{line}} = 0$) this expression reduces to

$$ V_{\text{cont}} = \frac{F_\ast + F_{\text{cs}} V_{\text{cs}}}{F_\ast + F_{\text{cs}}}, $$ (7.2)

$$ = f + (1 - f) V_{\text{cs}}, $$ (7.3)

where $f$ is the stellar flux as a fraction of the total continuum flux in the $K$-band (see Sect. 7.3.3). It is implicitly assumed that the visibility of the star (a point source) equals 1.
Figure 7.5: Top: Squared visibilities measured by AMBER in the E0G0H0 configuration (PA = 72–74°; see Table 7.1). The line-emitting region (|v| < 50) is delimited by vertical lines. Within this region, $V^2_{\text{line}}$ is plotted (dotted line). Average values for $V^2_{\text{cont}}$ (green) and $V^2_{\text{line}}$ (cyan, see text) are indicated with symbols. For each observation, a different symbol is used. Bottom: Average $V^2_{\text{cont}}$, $V^2_{\text{line}}$ values plotted as a function of baseline. The colored surface corresponds to the $V^2$ of a grid of single-Gaussian models with half width at half maximum (HWHM) as indicated by the colors. The best-fit models are indicated for the continuum-emitting region (green solid line) and the line-emitting region (cyan solid line). The fit to the stellar-flux-corrected continuum region ($V^2_{\text{cs}}$) is also plotted (orange dashed line).
7.4 RESULTS: AMBER INTERFEROMETRY

Using Eqs. (7.1) and (7.2), we derive $V_{\text{line}}$ and $\Delta \phi_{\text{line}}$ in terms of the observed quantities $V$, $\Delta \phi$, $V_{\text{cont}}$, and $F_{\text{norm}} = (F_{\text{line}} + F_{\text{cont}})/F_{\text{cont}}$; this derivation is done in Sect. 7.C. The visibility of the line emitting region can thus be disentangled from the continuum. Likewise, within the continuum, Eq. (7.3) can be used to disentangle $V_{\text{cs}}$ from the stellar contribution.

Figure 7.5 (top panel) displays the observed $V^2$ as a function of wavelength. The green symbols represent $V^2_{\text{cont}}$, measured as the mean value of $V^2$ across the range $500 < |v| < 1000 \text{ km s}^{-1}$. For the high-resolution observations, $V^2_{\text{line}}$ is computed (dotted line) and averaged (cyan symbols) over the central 8 wavelength bins ($|v| < 50 \text{ km s}^{-1}$, or two resolution elements). In the medium-resolution observations, no meaningful values of $V^2_{\text{line}}$ are retrieved, as the differential phase signal is very weak.

As expected, $V^2_{\text{line}} > V^2_{\text{cont}}$ in all baselines: line emission originates from a more compact region than the continuum. In order to derive absolute sizes, we compare the visibilities of both components to those of a simple Gaussian intensity distribution, see Sect. 7.D. This assumes that the continuum and line brightness distributions are well approximated by a Gaussian profile.

Figure 7.5 (bottom panel) shows the observed visibilities over a grid of Gaussian models as a function of baseline. The best-fitting models for $V^2_{\text{cs}}$ and $V^2_{\text{line}}$ have a half width at half maximum (HWHM) of $\theta_{\text{cs,mod}} = 3.4 \text{ mas}$ (1.7 AU; $\chi^2_{\text{red}} = 38.1$) and $\theta_{\text{line,mod}} = 1.5 \text{ mas}$ (0.8 AU; $\chi^2_{\text{red}} = 2.6$), respectively. The high $\chi^2$-value of the $V^2_{\text{cs}}$-fit results from a bad fit of the short-baseline visibilities, but is not considered problematic to derive global size estimates. This model is corrected for the stellar flux and falls off to $f^2 = 0.016$ instead of zero. These best-fit values are used as fiducial size parameters along the disk major axis in the model presented in Sect. 7.5.

7.4.2 Photocenter shifts

The differential phase is a proxy for the shift of the photocenter across the Br$\gamma$ line. It can be used to perform spectro-astrometry if the baselines sufficiently cover the dimensions in the $(u, v)$-plane. We use the three U2U3U4 observations, each with three baselines, which were taken with at most one month in between observations. These observations are selected to reduce the effect of systematical errors. Eventually, we check the solution for consistency with other observations. To convert the $\Delta \phi$-measurements to the photocenter displacement vector, $\mathbf{P} = (P_x, P_y)$, we follow Lachaume (2003). We set $\mathbf{P} = 0$ in the continuum, and assume that $CP = 0$ across the line.

For marginally resolved objects, and for small displacements, the differential phase $\Delta \phi_i$ approximates a linear projection of $\mathbf{P}$ along the baseline vector $\mathbf{B} = -2\pi |u_i, v_i|/\lambda$. From the nine measurements $\Delta \mathbf{\phi} = \{\Delta \phi_1, \Delta \phi_2, \ldots, \Delta \phi_9\}$ the displacement is obtained by performing a weighted linear least square fit:

$$\mathbf{P} = (\mathbf{B}^T \mathbf{W} \mathbf{B})^{-1} \mathbf{B}^T \mathbf{W} \Delta \mathbf{\phi},$$

where $\mathbf{W}$ is a $9 \times 9$ diagonal matrix containing the inverse squared errors on $\Delta \mathbf{\phi}$. We repeated this procedure for 21 velocity channels on the interval $v = (-210, 210) \text{ km s}^{-1}$, rebinned with a width of 20 km s$^{-1}$.
A RESOLVED, AU-SCALE GAS DISK AROUND THE B[e] STAR HD 50138

Figure 7.6: Top left: Differential phase measured over the three U2U3U4 baselines in three different observations. Overplotted are the data rebinned on $\Delta v = 20$ km s$^{-1}$ from -210 to 210 km s$^{-1}$, color-coded with their velocity. The yellow lines correspond to the astrometric solution, $P(\lambda)$. Top right: two-dimensional representation of the photocenter displacement, $P(\lambda)$, as a function of velocity across the Br$\gamma$ line. North is up, East is to the left. The (averaged) baselines of the U2U3U4 triplet are indicated on the bottom left. The dashed line corresponds to the orientation of the disk major axis ($\psi = 71^\circ$) as derived by BF11. Bottom: Astrometric solution, $P(\lambda)$ (yellow line), overplotted on the differential phase observations which were not included in the fit. The error bars correspond to the 1$\sigma$ spread in the continuum region.

The result is plotted in Fig. 7.6 (top right). There is an elongated structure along $PA \sim 70^\circ$, with an overall offset towards the NW with respect to the continuum. The structure is parallel to the disk major axis derived by BF11 and perpendicular to the polarization angle. The blue-shifted ($-200 \lesssim v < 0$ km s$^{-1}$) part of the line is offset towards the NE, while the red-shifted part ($0 \leq v < 200$ km s$^{-1}$) is offset towards the SW. The largest offsets are seen in the lowest velocity channels. This result suggests radially decreasing differential rotation around an axis of $\sim 160^\circ$. The result is consistent with
the $\Delta\phi$ measurements which were not included in the fit (Fig. 7.6, bottom), indicating that no additional asymmetries are resolved at this angular resolution.

The solution $P(\lambda)$ is a proxy for the first moment of the brightness map at wavelength $\lambda$. It is strictly a “center of gravity” of the line and continuum contributions to the brightness map, weighted by their respective fluxes. To obtain information on the absolute size and dynamics of the line emitting region, the contribution of the continuum emission must be subtracted from the solution (cf. the method in Sect. 7.4.1). However, given the very low S/N in $\Delta\phi$, it is not feasible to derive channel-to-channel photocenter shifts in the line. Instead, we use the parameters derived in this section as an input for a geometric model with which all the observables are reproduced. This is done in Sect. 7.5.

7.5 Geometric modeling

The results presented in Sect. 7.4 suggest the presence of an AU-scale gas disk around HD 50138. This interpretation is based on different subsets of the high-resolution AMBER-data: characteristic size estimates are based on short-baseline observations (Sect. 7.4.1), while the spectro-astrometry is based on long-baseline observations (Sect. 7.4.2). The latter result is consistent with the observations which were not used for the fit (Fig. 7.6, bottom). In this section, we aim to interpret all the interferometric data in terms of a single, self-consistent physical interpretation. To this end, we construct a geometric model, whose predictions are compared to the data.

The model configuration is presented in Sect. 7.5.1. The number of parameters is kept as small as possible. Rather than obtaining the best-fit values by brute-force optimization, we choose a more intuitive approach. Most of the parameters are set to a priori estimated values based on independent results. Three representative models are presented to illustrate the effect of adding or changing some of the parameters. We motivate these choices in Sect. 7.5.2. From this model, we calculate spectra, differential visibilities, and differential phases. We compare these to the data in Sect. 7.5.3, and discuss the constraints on and the degeneracies of the model parameters.

7.5.1 Model configuration

Our model consists of four physical components:

(i) a star;

(ii) a continuum-emitting disk;

(iii) a line-emitting disk;

(iv) a line-emitting spherical halo.

The star (with mass $M_*$) is simulated as a point source at the grid origin at a distance $d$ and with a fixed fraction $f$ of the total flux in the modeled wavelength domain. For the
circumstellar continuum emission, we adopt a single elliptical Gaussian distribution with as its parameters the HWHM along its major axis ($a_{\text{cont}}$), its orientation ($\psi$), and inclination ($i$). Both star and dust disk are centered at the origin. The gas disk is translated into a Br$\gamma$ image in different velocity channels across the line. Directed by the results of Sect. 7.4.2, we assume that the gas is distributed in a razor-thin rotating disk with a Keplerian velocity field:

$$
\nu(r) = \sqrt{\frac{GM_*}{r}}. 
$$

(7.5)

The gas disk has inner and outer radii $R_{\text{in}}$ and $R_{\text{out}}$, and has the same inclination and orientation as the continuum-emitting disk. We consider emission from the disk in the Br$\gamma$ line at $\lambda_0 = 2166.167$ nm from a flat disk. The emission measure depends on the local temperature and surface density. We parametrize the resulting radial surface brightness profile by a simple power law:

$$
B(r) = \left(\frac{r}{R_{\text{in}}}\right)^{-\alpha},
$$

(7.6)

where we fix $\alpha$ to match the observed Br$\gamma$ spectrum.

We have also investigated the effect of adding a spherical halo of radius $R_{\text{halo}}$ to the line emission model, to explain the variable emission at the systemic velocity. The
Table 7.2: Model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Obtained from</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\psi$ (N to E)</td>
<td>71°</td>
<td>BF11, spectro-astrometry (Sect. 7.4.2)</td>
</tr>
<tr>
<td>$i$</td>
<td>56°</td>
<td>BF11</td>
</tr>
<tr>
<td><strong>Continuum model</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f$</td>
<td>0.08</td>
<td>SED (Sect. 7.3.3)</td>
</tr>
<tr>
<td>$a_{\text{cont}}$</td>
<td>1.7 AU (3.4 mas)</td>
<td>$V_{\text{cs}}$ (Sect. 7.4.1)</td>
</tr>
<tr>
<td><strong>Keplerian gas disk</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_*$</td>
<td>6 $M_\odot$</td>
<td>BF09</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>2</td>
<td>Carciofi &amp; Bjorkman (2008)</td>
</tr>
<tr>
<td>$R_{\text{in}}$</td>
<td>0.1 AU (0.2 mas)</td>
<td>Width of spectral line profile</td>
</tr>
<tr>
<td>$R_{\text{out}}$</td>
<td>0.6 AU (1.2 mas)</td>
<td>$V_{\text{line}}$ (Sect. 7.4.1); line profiles (Fig. 7.3).</td>
</tr>
<tr>
<td>$R_{\text{halo}}$</td>
<td>--</td>
<td>3 AU (6 mas)</td>
</tr>
<tr>
<td>$\Delta v_{\text{halo}}$</td>
<td>--</td>
<td>0.6 AU (1.2 mas)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 AU (6 mas)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 km s$^{-1}$</td>
</tr>
</tbody>
</table>

The intensity at a physical radius $r$ is given by

$$I(r, \lambda) = \frac{B(r)}{\sqrt{2\pi\sigma}} \exp \left[-\frac{(\lambda - \lambda_0)^2}{2\sigma^2}\right], \quad (7.7)$$

where $\sigma$ is set by the spectral resolving power $\mathcal{R}$:

$$\sigma = \frac{\lambda_0}{2 \sqrt{2\ln 2} \mathcal{R}}. \quad (7.8)$$

The contribution of every pixel is calculated with high spectral resolution ($\Delta v = 0.5$ km s$^{-1}$). Channel maps are created by summing all contributions with a spectral bin width of $\Delta v = 10$ km s$^{-1}$. A selection of channel maps is displayed in Fig. 7.7. Every channel map is superposed on the continuum image; the two contributions are scaled to match the observed line peak to continuum ratio in the spectrum.

Simulated observables are obtained from the model images, as follows. The spectrum is calculated as the integrated flux of the individual channel maps. For every baseline used in the observations, complex visibilities were measured from the line and continuum maps. These were converted to observed quantities $V^2$ and $\Delta \phi$ by taking the norm and argument of Eq. (7.1). As the absolute calibration is uncertain, we compared squared differential visibilities $V_{\text{diff}}^2 = V^2 / V_{\text{cont}}^2$ between models and observations.
7.5.2 Model parameters

In this section we present the three sets of model parameters which we use to interpret the data. We motivate the \textit{a priori} estimates for eight parameters which are the same in all three models. These are the geometric parameters \(d, \psi, i\); the stellar parameters \(f\) and \(M_*\); the dust disk size, \(a_{\text{cont}}\); and the gas disk parameters \(R_{\text{in}}\) and \(\alpha\). Estimates are based on the spectroscopy results (Sect. 7.3) and on previous studies. Three parameters remain free: \(R_{\text{out}}\) and the halo parameters \(R_{\text{halo}}\) and \(\Delta v_{\text{halo}}\). From the parameter space spanned by these, we elect three representative models: a small gas disk (D1), a large gas disk (D2), and a small gas disk plus gas halo (DH). The disk outer radius \(R_{\text{out}}\) varies between models D1 and D2. Model DH is the same as D1, but with the additional parameters \(R_{\text{halo}}\) and \(\Delta v_{\text{halo}}\).

The adopted distance to the system is \(d = 500\) pc (van Leeuwen 2007). The dust continuum emission is modeled by an elliptical Gaussian. We adopt an orientation of the major axis, \(\psi = 71^\circ\), and an inclination angle, \(i = 56^\circ\), based on near- and mid-infrared continuum interferometry by BF11. The baselines used for the size estimates in Sect. 7.4.1 are almost parallel to \(\psi\). The best-fit value for the HWHM of the Gaussian fit to \(V_{\text{cs}}\) is 3.4 mas (1.7 AU); we thus set \(a_{\text{dust}}\) to this value.

The parameter \(f = 0.08\) was obtained from SED fitting (Sect. 7.3.3). The stellar mass is estimated by comparing \(L_*\) and \(T_{\text{eff}}\) to pre- and post-main-sequence evolutionary models (BF09; see also Schaller et al. 1992; Hosokawa et al. 2010); we adopt \(M_* = 6\) M$_\odot$.

The highest velocities in the line profile trace the disk inner radius. No emission is detected at velocities \(|v| > 230\) km s$^{-1}$, hence we assume \(R_{\text{in}} = 0.1\) AU.

Two important physical features which are to be constrained by the model are the apparent extent of the disk, and the presence of a halo. The (apparent) extent of the disk is determined by the combination of \(\alpha\) and \(R_{\text{out}}\). We adopt \(\alpha = 2\), which matches the observed Br$\gamma$ spectrum, and is also a typical value for a (Herbig) Be star disk (Carciofi & Bjorkman 2008; Eisner et al. 2010). The results of Sect. 7.4.1 yield a size of \(\sim 3.1\) mas for the line-emitting region along \(\psi\), corresponding to a radius of 0.8 AU. An independent estimate of the outer disk radius is derived from the double-peaked lines in the spectrum (Fig. 7.3). If these are a result of rotation, the peak-to-peak separation corresponds to the disk diameter (Horne & Marsh 1986). The average separation of \(\sim 200\) km s$^{-1}$ implies a disk outer radius of 0.5 AU. Based on these two estimates, we adopt \(R_{\text{out}} = 0.6\) AU. A model with \(R_{\text{out}} = 3\) AU is also calculated to show the effect of the apparent disk size on the observables. These models are referred to as D1 (the 0.6 AU disk) and D2 (the 3 AU disk).

Motivated by the variable emission at the systemic velocity, a third model, DH, is constructed with the same parameters as D1, but with the addition of a spherical halo. Its radius, \(R_{\text{halo}}\), is set to 3 AU, as this radius most accurately reproduces the observed \(V_{\text{diff}}^2\) values. The width of the spectral line profile is set to \(\Delta v_{\text{halo}} = 60\) km s$^{-1}$ to fit the observed emission.
7.5.3 Comparing observations with models

In Fig. 7.8 two representative observations (one with short AT baselines, one with long UT baselines) are shown. The D1, D2, and DH modeled spectra, visibilities and phases are overplotted. Figure 7.10 displays the same for all the observations. Model D1 correctly predicts the observed differential phase signatures (which was also suggested by Fig. 7.6, bottom). However, it produces a double-peaked spectral line profile, which is not observed. Moreover, the predicted differential visibilities are too high, implying that the emission is too compact with respect to the continuum. Model D2 (with larger outer gas disk radius) has a better fit to the spectra and visibilities, but a too high amplitude in the phase signal.

This discrepancy may be summarized as follows: the phases indicate Keplerian rotation at a compact (sub-AU) scale, but the visibilities indicate significant emission from larger (several AU) scales. Furthermore, the spectra indicate that the emission is not solely due to a rotating disk. This motivates the inclusion of a halo: model DH. The discrepancies are partly resolved by this model. The double peaks of the line are filled in; the differential phase signal of model D1 is retained, while the visibilities are scaled down to the levels of model D2. A mismatch between this model and the observations is the visibility drop at zero velocity, an effect of the halo’s large size.

Upon exploring the parameter space, we conclude that the eight fixed parameters are reasonably well constrained. The effect of changing $\psi$, $i$ and $a$ has been investigated; no other choice of these parameters leads to a better match with the observations. A degeneracy exists between $d$, $M_*$ and the size parameters in the model. For example, a lower adopted stellar mass has an effect similar to a shorter observing distance, or a larger disk inner radius. However, the observations are best reproduced with the initial set of values for $d$, $M_*$, and $R_{\text{in}}$, which are also consistent with independent results. The size parameters $R_{\text{out}}$, $R_{\text{halo}}$ following from these are consistent with the absolute size scales derived in Sect. 7.4.1.

The differential visibilities observed with baselines exceeding 50 m are overpredicted by all the models. This may indicate that at these size scales, the disk is less resolved than predicted by the (oversimplified) model. Alternatively, the low S/N in $V_{\text{cont}}$ may lead to a systematically underpredicted $V_{\text{diff}}$. A different choice for the parameter $f$ affects the value of $V_{\text{cont}}$ equally in all observations, see Eq. 7.3. The substructure within the visibility peak, which is predicted by the models, is not observed in any of the baselines. This may point to a source of emission at the systemic velocity less extended than the halo, like a binary companion. This is also a possible explanation for the photocenter offset between line and continuum (see Sect. 7.4.2), which is not predicted by our axisymmetric model. This is further discussed in Sect. 7.6.1.

Summarizing, the AMBER spectra, visibilities and phases are well reproduced by model DH: a 0.6 AU Keplerian disk and a 3 AU halo. The parameters are constrained within a reasonable range, and consistent with independent observational results. The predictive capability of the model beyond this general morphology is limited, as the system shows signs of complexity that are not well constrained by the available observations (e.g., non-axisymmetry, variability).
Figure 7.8: Two representative model fits. From top to bottom: spectrum, differential visibilities, differential phases and closure phase observed with a compact (left) and extended (right) AMBER array. Overplotted are the observables calculated from models D1 (0.6 AU disk, red line), D2 (3.0 AU disk, blue line) and DH (0.6 AU disk + 3.0 AU halo, green line). Figure 7.10 compares the results of the same models with all the AMBER observations.
7.6 Discussion

In this section, we discuss the main constraints obtained from the analysis of the data and the modeling. We first discuss the kinematics of the circumstellar gas as derived from our analysis and modeling. We also comment on the properties of the circumstellar dust disk. We then briefly review the signatures of binarity obtained from our and other observations. Finally, the implications of our results for the object’s evolutionary state are discussed.

7.6.1 Kinematics of the circumstellar gas

We find strong evidence for the presence of an AU-scale Keplerian gas disk around HD 50138. The visibilities in the Brγ line imply that most of the emission originates within 4 mas, which corresponds to 2 AU (Sect. 7.4.1). This is consistent with the near-infrared disk size estimates by BF11. Dust at the sublimation temperature (∼ 1500 K) is a likely source of the K-band continuum emission. A picture where gas emission dominates within the dust sublimation radius is consistent with the observed $V_{\text{line}}^2 > V_{\text{cont}}^2$ for all baselines. This is similar to what has been found in systems with a comparable dust SED (Kraus et al. 2008a; Eisner et al. 2010).

The differential phases show a signature of rotation around an axis of ∼ 160° (Sect. 7.4.2). The decrease in velocity with the distance to the center is consistent with a central mass of ∼ 6 $M_\odot$ at a distance to the observer of 500 pc. Evidence for a gas disk with the same orientation was found in spectropolarimetry (Bjorkman et al. 1998; Oudmaijer & Drew 1999). The inclination and orientation are consistent with the mid- and near-infrared continuum-emitting disk found by BF11. Similar evidence of a Keplerian velocity field has been found in interferometric studies of other (binary) B[e] systems (Kraus et al. 2012; Wheelwright et al. 2012b).

An additional, strongly variable emission peak at $v$ ∼ 0 and with $\Delta v$ ∼ 60 km s$^{-1}$ is seen in some lines (e.g., Brγ, O I). These lines alternate between double- and single-peaked profiles on timescales of days to years. This suggests the presence of an additional component in the system, or variable emission from the disk. Observations with temporal coverage at typical orbital timescales (i.e. weeks to months) are needed to constrain this possibility. We fit the component with a uniform line-emitting spherical halo. An optically thin halo has been included in physical models of Herbig stars to explain their near-infrared continuum emission (Vinković et al. 2006); in our model, it purely produces gas line emission.

Aside from a disk and halo, other possible geometries include infall or outflow, but are less likely. Infall is suggested by several He I, Mg II and Si II profiles, but the interpretation depends on the adopted systemic velocity (see Sect. 7.3.2). The spectral profile of the Brγ line does not show absorption components, nor does its velocity distribution resemble an infall geometry.

In pre-main-sequence systems of comparable mass, Keplerian rotation signatures have been found in the Brγ line (Kraus et al. 2008b, 2012). More commonly, however, this line traces outflow in a disk wind or jet (Malbet et al. 2007; Tatulli et al. 2007b;
The velocity is expected to increase as the material moves away from the source; in the case of HD 50138, a velocity decrease is observed. Also, asymmetries would exist between the red- and blue-shifted parts of the line emission, as the receding (red-shifted) jet lobe is blocked by the circumstellar disk (see Chapters 3–5). These are not observed. Finally, the outflow axis would be perpendicular to the polarization angle, which is not likely in a disk-jet geometry (Maheswar et al. 2002). The combination of a single-peaked profile and a spectro-astrometric rotation signature has been found in the CO lines of some protoplanetary disks (Bast et al. 2011; Pontoppidan et al. 2011; Brown et al. 2013). In these cases, the single peak is fitted by including an equatorial outflow component in the disk velocity field.

The three Keplerian disk models presented in Sect. 7.5 qualitatively reproduce all the observations. Neither of the “pure-disk” models D1 and D2 reproduce all the observed signatures; there is a mismatch between either the spectrum and the differential visibilities (in the case of D1) or the differential phase amplitudes (in the case of D2). Any solution to the discrepancies involves adding more parameters to the model, with a limited amount of constraints from the data. We partly resolved the discrepancies by adding a halo (model DH). The substructure in the visibility peaks produced by the models (not observed) indicates their limited predictive capability.

Another important result is the offset of the Brγ line emission towards the NW with respect to the continuum photocenter (Fig. 7.6, top right). This may indicate that the line-emission disk geometry is more complicated; for example, a flaring disk naturally induces a photocenter offset (see, e.g., Lagage et al. 2006). Alternatively (or additionally), an asymmetric continuum distribution (e.g., a disk rim, or binary companion) would cause an offset with respect to the line emission. A Keplerian gas disk may exist in case of a close binary scenario as a result of mass exchange. Further indications of binarity are the ambiguous spectral classification (Sect. 7.3.1) and variability, although pulsations may cause the latter (BF09, BF12).

The photocenter offset in the Hα line found by Baines et al. (2006) is in the same NW direction as the Brγ shift. In this part of the spectrum, however, the continuum is dominated by photospheric emission; therefore, these authors interpret the offset as a signature of a (wide) binary. A more thorough investigation of the near-infrared continuum visibilities and phases will contribute to resolving possible companion(s) or an asymmetric disk (Kluska et al., in prep.). Close companions may also be found or excluded by a spectroscopic monitoring campaign.

To summarize, most observed signatures are consistent with the presence of an AU-scale Keplerian disk plus gaseous halo. Signatures which are not accounted for are the absolute level of the long-baseline visibilities, the variability of the emission and the photocenter offset. Additional sources of emission (e.g. a binary companion) and/or a more complicated disk geometry are required to obtain a satisfactory explanation for all the data.
7.6.2 Dust disk

For dust SEDs like the one of HD 50138, the $K$-band emission is very likely dominated by a dust population near the sublimation radius ($R_{\text{sub}}$, Dullemond et al. 2001). The theoretical location of $R_{\text{sub}}$ (Eq. 1 in Dullemond & Monnier 2010) for this object is $1.5 - 4$ AU ($3-8$ mas) assuming a typical sublimation temperature of $T_{\text{dust}} = 1500$ K. This is consistent with the derived Gaussian HWHM of $\sim 1.7$ AU ($3.4$ mas) for the $K$-band continuum emission. Radiation from this hot component can account for the emission in excess of the photosphere from $1$ $\mu$m onwards (Fig. 7.4). If this is the case, however, a more complicated spatial structure than a Gaussian is expected for the near-infrared emission.

The shape of the infrared SED is reminiscent of Herbig stars with flat disks (“group II” in Meeus et al. 2001). For this particular group of SED, Acke et al. (2009) find an anti-correlation between the $7 \mu$m excess and the $[30/13.5]$ flux ratio in their sample of Herbig Ae/Be stars. These authors suggest that this may in general be a result of shadowing effects caused by an increased scale height of the inner disk.

The excess and slope of the HD 50138 SED follow this trend. The strong $7 \mu$m excess (5.9 mag) implies a large amount of $\sim 300 - 800$ K dust in the inner disk. The steep disk slope ($[30/13.5] = 0.78 \pm 0.04$) may be an effect of shadowing by the inner disk. According to the models by Acke et al. (2009, their Fig. 2), HD 50138 would require an inner disk scale height more than three times higher than the value predicted by hydrostatic equilibrium. The high luminosity results in a large dust sublimation radius, and therefore a low local gravity. This tends to increase the local scale height of the disk which can therefore be quite different from the inner disks of less luminous Herbig stars. Apart from Herbig stars, these types of SED are also seen in post-AGB stars, where the circumstellar dust at high scale heights is a result of mass loss through a stellar wind or — in most cases — binary interaction (de Ruyter et al. 2006; Gielen et al. 2008). The SEDs of these types of pre- and post-main-sequence objects are therefore indistinguishable. We will discuss this in the next section.

7.6.3 Evolutionary state

Our results contribute to answering the intriguing question: is HD 50138 a pre-main-sequence (i.e, Herbig B[e] star), main sequence or post-main-sequence object? Most of the characteristics are consistent with all of these possibilities. Taking all signatures into consideration, a main-sequence or post-main-sequence nature is deemed the most probable.

We find that the Br$\gamma$-emitting circumstellar gas has a rotation-dominated velocity field, most likely a disk. AU-scale Keplerian gas disks are found around both pre-main-sequence (Acke et al. 2005; Bagnoli et al. 2010; Weigelt et al. 2011; Kraus et al. 2012) and post-main-sequence (Bujarrabal et al. 2007; Wheelwright et al. 2012b) early-type stars, some of which are known binaries. In pre-main-sequence stars, an accretion column and outflows more commonly dominate the Br$\gamma$ emission (Eisner et al. 2010). The disks of post-main-sequence systems are expected to have a strong outflow component.
In the case of HD 50138, rotation dominates the velocity field, which is consistent with both a pre- and post-main-sequence nature.

The existence of a binary companion, as suggested by various signatures (photocenter offset, variable spectral type, variability of emission lines), is also consistent with either scenario. Close binary systems surrounded by dust disks are commonly seen in Herbig (Baines et al. 2006; Wheelwright et al. 2011; Garcia et al. 2013) and post-AGB (de Ruyter et al. 2006; Gielen et al. 2008; Kraus et al. 2013) systems. In the former case, the close binary may have formed by disk fragmentation (Krumholz et al. 2009). In the latter case, the dust disk is most likely the result of binary interaction, as discussed in Sect. 7.6.2. The SED does not enable us to distinguish between these scenarios. Thermal pulses and thus a post-AGB phase are excluded at the system's luminosity. Alternatively, the system could be a failed AGB star evolving into a sub-dwarf OB star (Heber 2009).

The emission component at $v \sim 0$, which appears and disappears in Brγ and other spectral lines, indicates a highly variable circumstellar geometry. Apart from our interpretation as a gaseous halo in Sect. 7.5, the emission may arise from a companion star or from slow-moving material in the accretion region close to the star. This component, as well as the many other detected variable signatures, may relate to shell phases and outbursts. These are also seen in both post- and pre-main-sequence objects (Crause et al. 2003, Kóspál et al. 2013, Chapter 5). Peculiar spectral profiles (He I, Mg II, Si II) indicate either infall or outflow, and are thus inconclusive regarding the evolutionary state. The spectral variability is poorly constrained because of the limited time coverage of the observations.

The infrared SED of HD 50138 also prevents distinguishing between a pre- and post-main-sequence nature (Sect. 7.6.2). Tracers of the completely different disk formation histories may be present in the shadowed outer disk ($\gtrsim 50$ AU). A pre-main-sequence star may leave a debris disk and planets (e.g., Quanz et al. 2013). However, if the object is pre-main sequence, its luminosity of $\sim 10^3 L_\odot$ indicates an age much younger than 1 Myr (Hosokawa et al. 2010). This timescale would be too short to form planets in the outer disk (Armitage 2010). In principle, planets could form in the evolved disks of post-AGB stars, as they have a similar structure; yet at these stellar masses, the disks are also short-lived (van Winckel 2003; Gielen et al. 2011). Sensitive high spatial resolution sub-mm images (e.g., taken with ALMA) would probe the size and structure of the outer disk, and the dynamical processes that occur there. This may constrain the disk age and hence the evolutionary state.

Additional heuristic arguments prefer a post-main-sequence nature. No evidence is found of a collimated jet, which would be a likely result of outbursts in pre-main-sequence objects (Chapters 4 and 5; Benisty et al. 2010b; Caratti o Garatti et al. 2013), although jet launching may be different towards higher stellar masses (Vaidya et al. 2011). The observed emission from high Paschen, Brackett and Pfund transitions are less commonly seen in young stars (Jaschek & Andrillat 1998; Lamers et al. 1998). The 2.3 $\mu$m CO emission is a common feature of young stellar objects in this mass range (Bik & Thi 2004; Ilee et al. 2013, Chapters 3, 4, and 6), but is not observed in HD 50138. The location of the object in the HRD (Fig. 1.5) would require high accretion rates if the object is young. However, save the ambiguous inverse P-Cygni profiles, no clear signatures...
of accretion are seen. Finally, the apparent isolation of the object from a star-forming region does not suggest a young age. Proper motion and distance measurements from the Gaia mission will better constrain the formation history.

Other B[e] systems for which AMBER observations have resolved the inner regions show evidence for binarity and gas disks. In most cases, these are confirmed evolved systems, whose circumstellar gas and dust disk is a likely result of the interaction between the stellar companions (HD 87643, Millour et al. 2009; MWC 300, Wang et al. 2012; HD 327083, Wheelwright et al. 2012b). In some cases, unambiguous evidence exists for an evolved evolutionary state (e.g., $^{13}$CO emission of HD 327083, Wheelwright et al. 2012a). Properties considered to be evidence of a pre-main-sequence nature are e.g., the absence of a binary companion (HD 85567, Wheelwright et al. 2013) or the absence of an outflow component in the disk (V 921 Sco, Kraus et al. 2012).

In summary, in the case of HD 50138, a post-main-sequence and binary nature is slightly favored over a pre-main-sequence nature, although many signatures are inconclusive. Given the extremely dynamical circumstellar environment, high-cadence spectroscopic and interferometric monitoring campaigns on timescales from days to years are the most promising strategy to further unravel this system.

### 7.7 Summary and Conclusions

In this chapter, we have presented observations of the gaseous circumstellar environment of HD 50138. Our main conclusions are listed below:

- Strong evidence is found that the Brγ emitting gas is distributed in a Keplerian rotating disk. This is suggested by the rotating and radially decreasing velocity field of the gas, which is distributed in an elongated structure aligned with independent estimates of the disk major axis.

- The gas emission originates from a smaller region (up to 3 AU) than the continuum emission attributed to dust. This is consistent with the inner few AU of the disk being too hot for dust to exist in equilibrium; in this region, the gas disk is expected to dominate the energy output.

- The interferometric observables can qualitatively be reproduced with a model of a geometrically thin Keplerian disk surrounded by a low-velocity halo and a more extended source of continuum emission. Supporting evidence for the existence of these components is given by the spectrum of the source.

- The strong variability of shell- or disk-dominated spectral line profiles indicates that significant changes take place in the system’s appearance on timescales as short as months, probably inhibiting a unified “fit” to all the datasets.

- The absolute offset of the photocenter in the continuum suggests intrinsic variability of the general geometry and/or binarity.
− No definitive conclusion on the evolutionary state could be reached. The system is possibly a binary, and bears much resemblance to both Herbig B[e] and post-AGB systems. Based on circumstantial evidence, the latter scenario is slightly favored.

After nearly a century of intensive research, HD 50138 continues to be an enigmatic object. In this study, we have for the first time mapped its inner environment and have discovered a rotating gas disk. Observations at a higher temporal resolution are key towards a better understanding of the evolutionary state of this highly dynamical system. The combined forces of interferometry and spectroscopy on high spatial and spectral resolution, and a broad wavelength domain, proves to be a very insightful strategy towards resolving these elusive objects.

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7.A AMBER: observations

Figure 7.9: Spectra, squared visibilities, differential phases and closure phase observed by AMBER. The top and bottom panels display the high- and medium-resolution data, respectively. Error bars are calculated as the $1\sigma$ noise level in the continuum. The array configurations, baseline lengths and position angles (N to E) are displayed in the top right corners of the panels. Colored squares in the bottom right corners connect properties of identical baselines.
7.B  AMBER: observations and models

Figure 7.10: Same as Fig. 7.9, but with $V_{\text{diff}}^2$ plotted instead of the absolute visibility. Overplotted are the observables calculated from models D1 ($R_{\text{out}} = 0.6$ AU, red line), D2 ($R_{\text{out}} = 3$ AU, blue line), and DH ($R_{\text{out}} = 0.6$ AU and spherical halo, green line).
7.C Line visibility

We derive expressions for $V_{\text{line}}$ and $\Delta \phi_{\text{line}}$ in terms of observed quantities. We assume that in a given spectral channel within the emission line, the brightness distribution can be described in terms of two components: the circumstellar continuum- and line-emitting regions. The following quantities are measured by AMBER:

- The normalized spectrum:

$$F_{\text{norm}} = \frac{F_{\text{cont}} + F_{\text{line}}}{F_{\text{cont}}}. \quad (7.9)$$

where $F_{\text{cont}}$ is the observed flux in the continuum (star plus circumstellar material) and $F_{\text{line}}$ the line flux.

- The differential phase $\Delta \phi$ and visibility $V$, which – assuming that $F_{\text{cont}}$ is constant across the line region – are related by rewriting Eq. (7.1) as:

$$V e^{i \Delta \phi} = \frac{V_{\text{cont}} + (F_{\text{norm}} - 1)V_{\text{line}} e^{i \Delta \phi_{\text{line}}}}{F_{\text{norm}}}, \quad (7.10)$$

where $V_{\text{cont}}$ is the observed value of $V$ in the continuum, and

$$\Delta \phi = \phi - \phi_{\text{cont}}, \quad (7.11)$$

$$\Delta \phi_{\text{line}} = \phi_{\text{line}} - \phi_{\text{cont}}. \quad (7.12)$$

We can rewrite this equation and solve for line visibilities and differential phases. We first split the equation into real and imaginary parts and eliminate $V_{\text{line}}$:

$$F_{\text{norm}} V \cos \Delta \phi = V_{\text{cont}} + (F_{\text{norm}} - 1)V_{\text{line}} \cos \Delta \phi_{\text{line}}, \quad (7.13)$$

$$F_{\text{norm}} V \sin \Delta \phi = (F_{\text{norm}} - 1)V_{\text{line}} \sin \Delta \phi_{\text{line}}, \quad (7.14)$$

$$\frac{F_{\text{norm}} V \cos \Delta \phi - V_{\text{cont}}}{\cos \Delta \phi_{\text{line}}} = \frac{F_{\text{norm}} V \sin \Delta \phi}{\sin \Delta \phi_{\text{line}}} \quad (7.15)$$

Solving for $\Delta \phi_{\text{line}}$:

$$\Delta \phi_{\text{line}} = \arctan \left( \frac{F_{\text{norm}} V \sin \Delta \phi}{F_{\text{norm}} V \cos \Delta \phi - V_{\text{cont}}} \right), \quad (7.16)$$

and from Eq. (7.14):

$$V_{\text{line}} = \frac{F_{\text{norm}} V \sin \Delta \phi}{(F_{\text{norm}} - 1) \sin \Delta \phi_{\text{line}}}. \quad (7.17)$$
7.D Visibility of a Gaussian distribution

Consider a normalized, one-dimensional Gaussian intensity profile with HWHM = $\theta$ along the radial coordinate $\rho$:

$$I_{\text{Gauss}}(\rho) = \frac{2}{\sqrt{2\pi \ln 2}} \exp\left(\frac{-\ln 2 \rho^2}{\theta^2}\right).$$

(7.18)

According to the Van Cittert-Zernike theorem, the visibility is the Fourier transform of the intensity distribution. The Fourier transform of a Gaussian is also a Gaussian; therefore the visibility function adopts the following form:

$$V_{\text{Gauss}}(B/\lambda, \theta) = \exp\left(\frac{-(\pi \theta B/\lambda)^2}{\ln 2}\right),$$

(7.19)

where $B/\lambda$, the baseline length in wavelength units, is the conjugate coordinate to $\rho$. 