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Letter to the Editor

The 2008 outburst in the young stellar system Z CMa★

I. Evidence of an enhanced bipolar wind on the AU-scale

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ABSTRACT

Context. Accretion is a fundamental process in star formation. Although the time evolution of accretion remains a matter of debate, observations and modelling studies suggest that episodic outbursts of strong accretion may dominate the formation of the central protostar. Observing young stellar objects during these elevated accretion states is crucial to understanding the origin of unsteady accretion.

Aims. Z CMa is a pre-main-sequence binary system composed of an embedded Herbig Be star, undergoing photometric outbursts, and a FU Orionis star. This system therefore provides a unique opportunity to study unsteady accretion processes. The Herbig Be component recently underwent its largest optical photometric outburst detected so far. We aim to constrain the origin of this outburst by studying the emission region of the HI Br_γ line, a powerful tracer of accretion/ejection processes on the AU-scale in young stars.

Methods. Using the AMBER/VLTI instrument at spectral resolutions of 1500 and 12 000, we performed spatially and spectrally resolved interferometric observations of the hot gas emitting across the Br_γ emission line, during and after the outburst. From the visibilities and differential phases, we derive characteristic sizes for the Br_γ emission and spectro-astrometric measurements across the line, with respect to the continuum.

Results. We find that the line profile, the astrometric signal, and the visibilities are inconsistent with the signature of either a Keplerian disk or infall of matter. They are, instead, evidence of a bipolar wind, maybe partly seen through a disk hole inside the dust sublimation radius. The disappearance of the Br_γ emission line after the outburst suggests that the outburst is related to a period of strong mass loss rather than a change of the extinction along the line of sight.

Conclusions. Apart from the photometric increase of the system, the main consequence of the outburst is to trigger a massive bipolar outflow from the Herbig Be component. Based on these conclusions, we speculate that the origin of the outburst is an event of enhanced mass accretion, similar to those occuring in EX Ors and FU Ors.

Key words. circumstellar matter – stars: variables: T Tauri – herbig Ae/Be – stars: winds – outflows – methods: obsevational – stars: individual: Z CMa – techniques: interferometric

1. Introduction

Accretion plays an important role in star and planet formation. For many years, it was considered to be a slow quasi-stationary process (e.g., Stahler 1988), occurring mostly through a viscous disk ending in its inner part by a boundary layer with the star (e.g., Bertout et al. 1988) or by magnetospheric funnels (e.g., Koenigl 1991; Calvet & Hartmann 1992). However, this scenario has been challenged by observations (e.g., Kenyon et al. 1990; Evans et al. 2009) that suggest that the accretion process could be time-variable and occur quickly by means of short high mass accretion rate bursts. Studying the very inner region of a young stellar object that is known to experience episodic photometric outbursts is thus of prime importance to understand the role of accretion in the formation of the star and its environment.

Z CMa is a pre-main-sequence binary with a separation of 0.1″ (Koresko et al. 1991; Barth et al. 1994) located at a distance estimated from 930 to 1150 pc (e.g., Clariá 1974; Kaltcheva & Hilditch 2000). The primary, embedded in a dust cocoon, was identified as a Herbig Be star based on spectropolarimetry (Whitney et al. 1993). It is surrounded by an inclined disk, possibly a circumbinary disk, as inferred from millimeter observations (Alonso-Albi et al. 2009), and dominates the infrared continuum and total luminosity of the system. In contrast, the secondary is the major source of continuum emission at visual wavelengths. Although the secondary has not undergone

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a large outburst this century, it was identified as a FU Or object based on its broad double-peaked optical absorption lines, which are typical of a circumstellar disk that undergoes a strong accretion, and spectral type of F-G (Hartmann et al. 1989). In the past twenty years, the Z CMa system exhibited repeated brightness variations, of ~0.5–1 visual magnitude, which were attributed to the Herbig Be star (e.g., van den Ancker et al. 2004). Z CMa is clearly associated with a bipolar outflow that extends to 3.6 pc along PA ~ 240° (Poetzel et al. 1989; Evans et al. 1994). Garcia et al. (1999) detected a $1'' \times 0.24''$ micro-jet in the [OI] 6300 Å line in the same direction, and concluded that the optical emission-line spectrum and the jet are associated with the primary. However, the innermost environments of the Z CMa components have been poorly studied. Two broad-band interferometric measurements have been obtained, allowing only characteristic sizes of the K-band continuum emission to be derived (Monnier et al. 2005; Millan-Gabet et al. 2006).

In January 2008, Z CMa's brightness increased by about two visual magnitudes (Grankin & Artemenko 2009), representing the largest outburst observed in the past 90 years. Based on spectropolarimetric observations, Szeifert et al. (2010) concluded that this outburst is associated with the Herbig Be star.

The study presented in this paper is part of a large observational campaign targeting Z CMa during this outburst that aims to understand its origin (Bonnefoy et al., in prep.; Bouvier et al., in prep.; Ratzka et al., in prep.; Whelan et al., in prep.). The overall spectral energy distribution of the system is strongly modified during the outburst at wavelengths shorter than 10 μm (Bonnefoy et al., in prep.; Ratzka et al., in prep.), which indicates that the outburst originates close to the star. To directly probe the morphology of the hot gas in the inner AUs, we took advantage of the spatial and spectral resolution available at the VLTI to perform μ-arcsecond spectro-astrometry. We resolved the K-band emission of the hot gas surrounding *each* star at the milliarcsecond resolution. This paper reports the first spatially *and* spectrally resolved observations in Br_γ of a young star. We also observed the binary system after the outburst. In Sect. 2, we present the observations and the data processing. In Sects. 3 and 4, we describe and discuss the results.

2. Observations and data processing

Z CMa was observed at the Very Large Telescope Interferometer (VLTI; Schöller 2007), using the AMBER instrument that allows the simultaneous combination of three beams in the near-infrared (Petrov et al. 2007). The instrument delivers spectrally dispersed interferometric observables (visibilities, closure phases, differential phases) at spectral resolutions up to 12 000.

In the following, we present K-band observations taken in the medium spectral resolution mode (MR; $R \sim 1500$) with the 8.2 m Unit Telescopes (UTs) as well as with the 1.8 m Auxiliary Telescopes (ATs), and in the high spectral resolution mode (HR; $R \sim 12\,000$) with the ATs. The data were obtained within programs of guaranteed time, Director's Discretionary Time, and Open Time observations. Z CMa was observed with 11 different baselines of 4 VLTI configurations, during 5 nights in December 2008 and one night in January 2010. The longest baseline is ~120 m corresponding to a maximum angular resolution of 3.7 mas. A summary of the observations presented in this paper is given in Table 1. With the UTs, the observations are coupled with the use of adaptive optics and the resulting field of view ranges from 50 to 60 mas. This allowed us to spatially resolve the binary and obtain *separate* measurements of the FU Or and the Herbig Be. In contrast, the ATs field-of-view, ranging from 230 to 280 mas, includes both stars and the interferometric signal results from both emissions. In addition to Z CMa, calibrators (HD 45420, HD 60742, HD 55137, HD 55832) were observed to correct for instrumental effects. All observations were performed using the fringe-tracker FINITO (Le Bouquin et al. 2008).

Table 1. Log of the observations. R is the spectral resolution.

Date	Baseline	Projected length (m)	Position angle (°)	R	
05/12/08	D0-G1	69	137	1500	FUOr+HBe
07/12/08	K0-G1	89	28	12 000	FUOr+HBe
09/12/08	K0-G1	88	24	12 000	FUOr+HBe
15/12/08	U2-U3	44	35	1500	
	U3-U4	62	107		
	U2-U4	86	78		
16/12/08	U1-U2	56	35	1500	
	U2-U4	77	88		
	U1-U4	120	66		
10/01/10	D0-G1	71	133	1500	FUOr+HBe

Notes. "FUOr+HBe" specifies when the binary is in the field of view.

The data reduction was performed following standard procedures described in Tatulli et al. (2007) and Chelli et al. (2009), using the `amdlib` package, release 2.99, and the `yorick` interface provided by the Jean-Marie Mariotti Center[1]. Raw spectral visibilities, differential phases, and closure phases were extracted for all the frames of each observing file. A selection of 80% of the highest quality frames was made and consecutive observations were merged to enhance the signal-to-noise ratio. The accuracy of the wavelength/velocity calibration is ~50 km s^{-1}. Because the K-band continuum measured by the ATs (due to both stars) is very resolved on long baselines ($V \sim 0$), the observations obtained on the G1-A0 and K0-A0 baselines could not be exploited. The absolute value of the visibilities obtained with the UT baselines could not be determined due to random vibrations of the telescopes. However, this issue affects all spectral channels in the same way, and does not modify our conclusions.

3. Results

We recall that the visibilities provide information about the spatial extent of the emission, and decrease as the extension increases. Differential phases provide a measurement of the photocenter displacements across the sky, projected along the baseline direction. They can therefore be converted into differential spectro-astrometric shifts. They are measured relative to the continuum, for which we assume a zero phase. Finally, the closure phases are related to the asymmetry of the brightness distribution (e.g., they are null for a point-symmetric object).

We show in Figs. 1 and 2 a subsample of the observations that illustrate the main characteristics of the data. Since the absolute values of the visibilities measured with the UTs are unknown, we normalized the continuum values to 1 – even though the emission is resolved. The left and middle columns of Fig. 1 present examples of the MR observations obtained with the UTs for each star during the outburst. Each column includes a spectrum (normalized to the continuum), squared visibilities, differential phases, and closure phases. For the FU Or (left panels),

[1] http://www.jmmc.fr

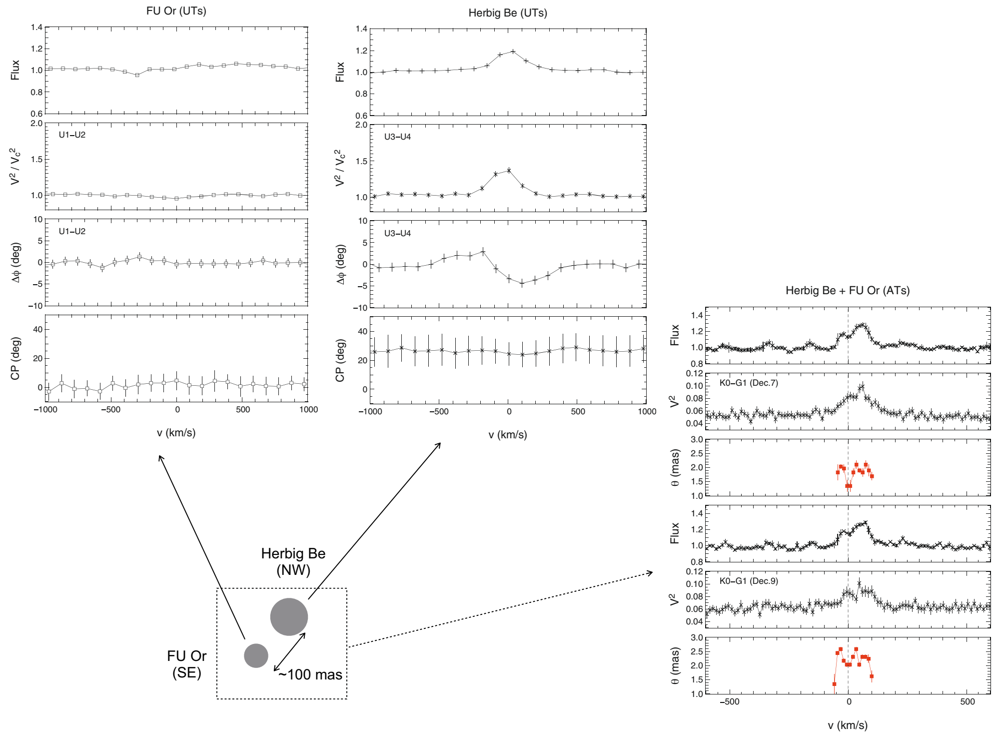

Fig. 1. Interferometric measurements of the Z CMa binary system in December 2008. The binary system is sketched at the bottom left. *Left panels*: MR spectrum, squared visibilities (normalized to the continuum ones, V_c^2), differential phases ($\Delta\Phi$), and closure phases (CP) measured for the FU Or with the UTs during the outburst. *Middle panels*: same for the Herbig Be. *Right panels*: ATs observations that include both stellar emissions in its field of view: HR spectra, visibilities, and the characteristic sizes of the Br_γ emission (see text for details).

within the error bars, the spectrum shows Br_γ in neither emission nor absorption. Consequently, no change in the visibilities or phases across the line is expected/seen. In contrast, the Herbig Be star exhibits a clear Br_γ line in emission (middle panels), although at this spectral resolution ($\Delta v \sim 200$ km s^{-1}), the line is not spectrally resolved. The visibility increases through the line and the differential phases produce an S-shape variation. The closure phases differ from zero, with values of $25° \pm 12°$. The phase, line, and visibility signals are present from ~–600 to 500 km s^{-1}, although because of the low line-to-continuum ratio in the extended wings, the flux and visibilities appear narrower. Within the large errors, no variation in the closure phases is detected across the line.

The right part of the figure shows measurements obtained with the ATs, i.e., with both stars in the field of view. In this case, the level of continuum is determined by both stellar components. These panels present observations obtained in HR. In this case, the line is spatially and spectrally resolved ($\Delta v \sim 25$ km s^{-1}), and the spectra exhibit a clear double-peaked and asymmetric profiles, with less emission at blueshifted velocities. The spectral visibilities present a similar profile.

Finally, Fig. 2 compares the spectra and the visibilities obtained during and after the outburst: the emission line, and the signature in the visibilities, disappear after the outburst. Plotted within a large velocity range, the visibilities show a typical signature of binarity (i.e., a cosine modulation), in agreement with the system main characteristics (separation, position angle, flux ratio; Bonnefoy et al., in prep.).

From the visibilities, one can locate the emission at each velocity and distinguish between various scenarios capable of producing the line. The visibility increase within the line implies that the Br_γ emitting region is more compact than the one responsible for the continuum. To derive the characteristic sizes of the region emitting Br_γ only, for each spectral channel of the HR measurements, one has to substract the underlying continuum to first determine the visibility of the line only (Weigelt et al. 2007). These estimates can only be performed using the data gathered with the ATs, for which reliable absolute values for the Br_γ visibilities are obtained. Using a model of an uniform ring, the emission in the line has a typical extension (ring diameter) of ~1.6 mas at zero velocity, and ~2.5 mas at higher velocities (~100 km s^{-1}), i.e., from ~1.5 to ~2.6 AU, depending on the distance. As the continuum emission measured with the ATs includes both stars, it is not direct to establish the typical size of the Herbig Be continuum. In contrast, the UTs data include only one stellar component. Although no absolute visibility values can be obtained, size ratios between the line and the continuum can be derived. Using the sizes previously estimated for the line from the ATs data, typical sizes of ~3.4 mas (~3.6 AU) for the Herbig Be K-band continuum can be determined, in agreement with the previous estimate (~3.9 mas in 2004; Monnier et al. 2005). Considering a dust sublimation temperature around 1500–2000 K (Pollack et al. 1994), and the stellar properties determined by van den Ancker et al. (2004), the inner edge of the dusty disk must be located at ~4–7 AU, in agreement with our findings. An asymmetry in the inclined inner disk could explain the non-zero closure phases measured at a level similar to other Herbig AeBe stars (Kraus et al. 2009; Benisty et al. 2010).

The differential phases $\Delta\Phi$ can be expressed in terms of photocenter displacements p (in arcseconds), following Lachaume (2003), given by $p = -2\pi\Delta\Phi/B\lambda$, where λ and B are the wavelength and the projected baseline length of the observations, respectively. p is the projection along the baseline direction, of the 2D photocenter vector $\boldsymbol{p}$ in the plane of the sky (i.e., of a spectro-astrometric signal). We fitted all the differential phases along the 6 available baselines with a single vector $\boldsymbol{p}$, independently of each spectral channel. The results are presented in Fig. 3. The left panels show the differential phases and the best solution for $\boldsymbol{p}$. The middle plot gives $\boldsymbol{p}$ in a 2D map of the plane of the sky. Clear asymmetric displacements, up to ~150 μ-arcseconds, are observed, both at red-shifted and blue-shifted velocities. In this case, $\boldsymbol{p}$ accounts for the emission of both the line and the

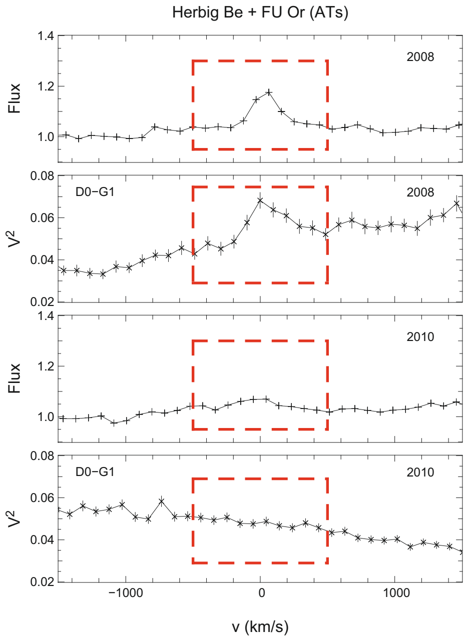

Fig. 2. MR normalized spectra and visibilities during (2008) and after the outburst (2010). The slopes of the visibility curves depend on the binary characteristics and on the observing set up, that differs in the two observations. Note the disappearance of the Br_{γ} line signature in the spectra and the visibility after the outburst (red dashed squares).

continuum. Substracting the continuum contribution to determine the photocenter displacements, $\boldsymbol{p}_{Br_{\gamma}}$, due to the line only, is difficult, as it has to be done in the complex visibility plane. We provide such an attempt in the velocity range where the line is clearly detected ([–350; 350] km s^{-1}, with line-to-continuum ratio larger than 1.05). As can be seen in Fig. 3, right, the displacements are much larger (up to ~1 mas) with the largest measured at the highest velocities, and appear more spread. Nonetheless, the observed asymmetry is still consistent with the closure phase measurements that show no change through the line, within the large errors.

4. Evidence of a bipolar wind

As has already been discussed in previous studies (Kraus et al. 2008; Eisner et al. 2009), the Br_{γ} line could be emitted by a variety of mechanisms, such as accretion of matter onto the star, in a gaseous disk, or in outflowing matter. The spectra obtained at high spectral resolution show a double-peaked and asymmetric profile that can be interpreted in the context of the formation of optically thick lines in a dense environment with a temperature gradient (Cesaroni 1995; Kurosawa et al. 2006).

Formation of the Br_{γ} line in an infalling envelope of gas can be ruled out. Considering that the line excitation temperature increases towards the star, if the line is emitted in infall of matter, or accretion flows, the profile would be double peaked but with an opposite asymmetry to what is observed (Fig. 1, right; i.e., with a lower emission at redshifted velocities; see Hartmann et al. 1994; Walker et al. 1994). In addition, in that case, the smallest extension and photocenter displacements would be expected at the highest velocities, which is in disagreement with our findings (see Figs. 1 and 3).

The possibility that the Br_{γ} line forms in the hot layers of the gaseous disk can also be ruled out. If one considers that the circumstellar disk surrounding the Herbig Be star is perpendicular to the large-scale jet at PA ~ 240°, it would be expected that the velocities projected onto the line of sight cancel out along the semi-minor axis, while large spectro-astrometric displacements are seen along this axis at high velocities (Fig. 3). Apart from this, the displacements increase with velocity while Keplerian rotation should behave in the opposite way, and a phase signal is measured up to high velocities (~500 km s^{-1}), which are much larger than the expected Keplerian velocities (~100–120 km s^{-1} at ~1 AU). It therefore seems unlikely that the Br_{γ} line is emitted in the disk.

We consider that the most likely origin of the Br_{γ} emission is a wind. Strong winds are expected to take place in massive Herbig Be (Nisini et al. 1995; Malbet et al. 2007), and could be responsible for the Br_{γ} emission. The double peaked and asymmetric line profile is consistent with outflowing matter emitting in optically thick lines (Hartmann et al. 1990). The visibilities and the 2D maps of the astrometric signal also support this conclusion as the blue- and redshifted emissions are located on each side of the possible disk position angle, with the largest Br_{γ} displacements and characteristic sizes being derived at higher velocities. Our observations suggest that the disk is slightly inclined, to allow both red- and blueshifted emissions to be seen. We may be seeing the emission from a wind partly through an optically thin inner hole in the optically thick dusty disk (Takami et al. 2001; Whelan et al. 2004). Alternatively, if the inner gaseous disk were optically thick, we may be seeing the redshifted emission through a much smaller hole and via scattering on the disk surface. Whether the innermost disk is optically thick or not cannot be determined with our observations and no reliable estimate of the mass accretion rate exists for such high mass young stars. However, the presence of the CO overtone lines in emission (Bonnefoy et al., in prep.) is indicative of a much lower mass accretion rate than those derived for FU Ors ($\leq 10^{-5}$ $M_{\odot}$ yr^{-1}; Calvet et al. 1991; Carr 1989). At the spatial resolutions provided by the VLTI, we trace the regions close to the inner disk hole and it is therefore unsurprising that we could detect redshifted emission, while on scales of 10–100 AU, the redshifted lobe is obscured by the circumstellar disk (Poetzel et al. 1989; Garcia et al. 1999; Whelan et al., in prep.). During this outburst, deep blueshifted absorption was detected in the Balmer lines from zero velocity to ~700 km s^{-1}, in addition to the absence of redshifted emission at similar velocities (Szeifert et al. 2010; Bouvier et al., in prep.), supporting our conclusion that there is a strong wind in the Herbig Be.

Could our new observations be tracing the inner parts of the parsec scale outflow? As shown in Fig. 3, the astrometric signal is detected at a slightly different position angle and at these spatial scales, it is unlikely that the jet is already collimated. Our observations exclude a fully spherical wind since in that case no displacement would be expected between the redshifted and blueshifted emission lobes. The derived spectro-astrometric signatures favor a bipolar wind, maybe unrelated to the jet, but can not determine whether its geometry is that of a disk-wind or a stellar wind.

After detecting the same level of optical polarisation in both continuum and spectral lines along a position angle roughly perpendicular to the large-scale jet, Szeifert et al. (2010) concluded that this outburst is related to a change in the path along which the photons escape from the dust cocoon. The disappearance of the Br_{γ} emission line, with respect to the continuum, after the outburst, suggests that its emission is related to the outburst. A strong mass ejection event could account for the deep blueshifted absorption features seen in the Balmer lines that are emitted

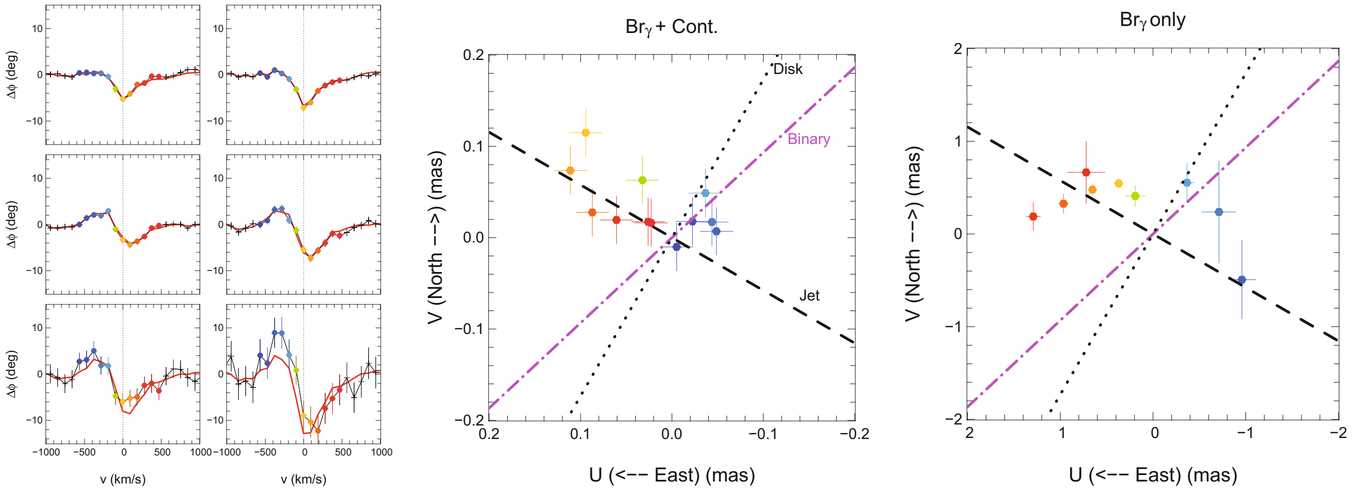

Fig. 3. *Left*: differential phases measured with the UTs (black crosses and lines). The dots in different colors represent various velocity channels, from dark blue (for $v \sim -600$ km s^{-1}) to dark red (for $v \sim +500$ km s^{-1}). The red line is the 2D astrometric solution $\boldsymbol{p}(\lambda)$. *Middle*: 2D representation of $\boldsymbol{p}(\lambda)$ within –600 and 500 km s^{-1}. The different colors code the velocity channels as represented in *the left panel*. The position angles of the binary (dashed-dotted line), of the large-scale jet (dashed line) and the direction perpendicular to the jet (dotted line) are overplotted. *Right*: same for $\boldsymbol{p}_{\mathrm{Br}_\gamma}(\lambda)$, after substraction of the continuum contribution. This was done within a narrower interval (–350 to 350 km s^{-1}) because of the low line-to-continuum ratio in the wings.

close to the star as well as for the Br$_\gamma$ line emitted in outer layers of the wind. Outside the outburst, the wind disappears or is more likely to be maintained at a much smaller mass loss rate. Based on these conclusions, one can speculate about the origin of the outburst, as being driven by an event of enhanced mass accretion, similar to the EX Ors and FU Ors outbursts (Zhu et al. 2010). In that case, this would suggest a strong link between mass accretion and ejection during the outburst, probably coupled with a magnetic field as in lower-mass young stars.

5. Conclusions

We have presented spatially and spectrally resolved interferometric observations of the K-band emission in the Z CMa system. These observations were performed during the largest photometric outburst detected so far, that occurred in the innermost regions of the Herbig Be star.

We found that the Br$_\gamma$ line profile, the astrometric signal, and the characteristic sizes across the line are inconsistent with a Keplerian disk or with infall of matter. They are, instead, evidence of a bipolar wind seen through a disk hole, inside the dust sublimation radius. The disappearance of the Br$_\gamma$ emission line after the outburst suggests that the outburst is related to a period of strong mass loss. Based on these conclusions, we have speculated that the origin of the outburst is an event of enhanced mass accretion, and that it does not result from a change in the system obscuration by dust. If this were valid, our results would suggest that the link between mass accretion and ejection as observed for quiescent T Tauri stars can also be at play in more massive young stars, and in high-accretion states.

Finally, this paper illustrates the great potential of the combination of spectro-astrometric and interferometric techniques for observing structures on μ-arcsecond scales.

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