Part 3

Imaging Techniques

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From Interacting Binaries to Exoplanets: Essential Modeling Tools
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Binaries and Multiple Systems Observed with the CHARA, NPOI, SUSI and VLTI Interferometric Eyes

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Abstract. In this review I will present recent results between 2007 and 2011 based on interferometric observations of binaries and multiple systems with the VLTI, NPOI, SUSI and CHARA instruments. I will also explain the kind of constraints an interferometer can provide in order to better understand the physics of multiple systems.

Keywords. stars: binaries (including multiple): close, stars: circumstellar matter, stars: stars: fundamental parameters, stars: imaging, stars: kinematics, stars: winds, outflows, stars: rotation, stars: mass loss, stars: imaging, techniques: interferometric

1. Introduction

Interferometry of binaries and multiple systems is a very active and attractive research field and more than 53 papers with the keywords "interferometry + binarity," excluding radio observations, were found between 2007 and 2011 using the Astrophysics Data System (ADS). These papers were arbitrarily "classified" in various themes, namely orbits (10 papers), fundamental parameters (13), model fitting (14), interacting binaries (11) and image reconstruction (5). These five themes are actually certainly biased due to angular resolution of a few milli-arsecond (mas) and magnitude limitations on the order of 6-7 of current ground-based optical interferometers. Note also that interferometric techniques are really fruitful and seem now in a mature age with growing results on direct imaging of circumstellar disks and stellar surfaces.

The first question to answer is: what can you do with an interferometer when observing a multiple system? We have identified 6 main topics, from the simplest case to more elaborate and complicated studies:

- Astrometry with precise orbits determination.
- Measurement of uniform disk, i.e. stellar photospheres and fundamental parameters.
- Measurements of limb darkened stellar surfaces.
- Kinematics of interacting binaries or circumstellar disks.
- Model fitting.
- Image reconstruction.

We must also stress that binary or multiple-system observations are strongly wavelength and time dependent, and also the important role played by amateur astronomers in the spectroscopic and photometric long-term monitoring, or "alert" mode, of some interesting targets, see for instance the BeSS database†. In this review paper, I will present an arbitrary selection of recent results obtained thanks to the CHARA, NPOI, SUSI and VLTI interferometers by following these 6 previously defined topics. Thus, the paper has the following structure: In Sect. 2, we present results of orbit determinations using very accurate interferometric measurements. In Sect. 3, we describe how an interferometer can be used to determine fundamental stellar parameters. Sect. 4 is dedicated to the model fitting of interferometric data. In Sect. 5, we illustrate recent image reconstructions of β Lyrae and ϵ Aurigae binary systems; and in Sect. 6, the main conclusions are drawn.

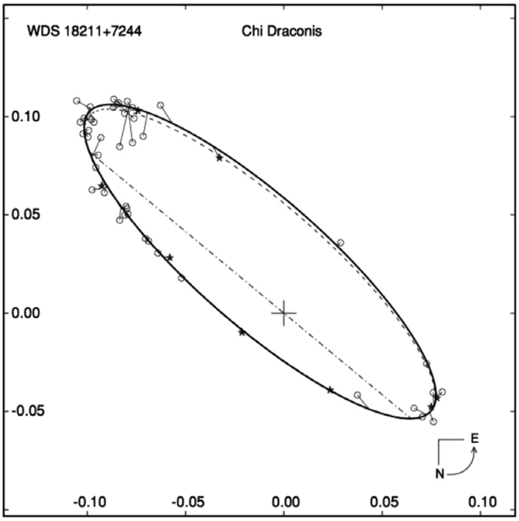

Figure 1. Orbit plot for χ Draconis by Farrington *et al.* (2010) using the CHARA interferometer

2. Orbit determination

On of the more obvious ways of determining a precise orbit for multiple systems is the use of interferometric data. The first measurements were done thanks to speckle-interferometry, see for instance Labeyrie (1970), but this technique is roughly limited to separations $\geqslant$ 30 mas, and more recently long baseline interferometry was successfully used for the same purpose. For instance, the precise orbits of χ Draconis HD 170153 SB2 (F8IV-V + late-G/early-K dwarf) with visual orbit, $m_v = 3.57$, $\pi = 124.11$ mas, P $\sim$ 281 days, was obtained by Farrington *et al.* (2010) using the CHARA interferometer. Using the orbital elements calculated in this paper and the most recent mass ratio calculated from Nordström *et al.* (2004), they obtained masses of $M_P = 0.96 \pm 0.03\ M_\odot$ and $M_S = 0.75 \pm 0.03\ M_\odot$, which fall below expected ranges for even the latest F-stars (see Fig. 1). This technique was also used for more complicated systems as σ^2 Coronae Borealis by Raghavan *et al.* (2009) with the CHARA interferometer. This system is composed of two Sun-like stars of roughly equal mass in a circularized orbit with a period of 1.14 days. The long baselines of the CHARA array have allowed them to resolve the visual orbit for this pair, the shortest-period binary yet resolved interferometrically, and enabling them to determine component masses of $1.137 \pm 0.037\ M_\odot$ and $1.090 \pm 0.036\ M_\odot$. This pair is the central component of a quintuple system, along with another similar mass star, σ^1

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CrB, in a $\sim$ 730 year visual orbit, and a distant M-dwarf binary, σ CrB C, at a projected separation of $\sim$ 10'. Finally to illustrate this technique, it is also possible to accumulate measurements from various interferometers, which was done by Kraus *et al.* (2009) by combining IOTA, NPOI and VLTI data to obtain a very precise orbit of the nearby high-mass star binary system θ^1 Ori C. Their new astrometric measurements have shown that the companion has nearly completed one orbital revolution since its discovery in 1997. The derived orbital elements imply a short-period (P $\sim$ 11.3 yr) and high-eccentricity orbit (e $\sim$ 0.6) with periastron passage around 2002.6.

3. Fundamental parameters

In the following, I will present a selection of recent results on the determination of fundamental parameters. Nevertheless, we first need to define what are these parameters. From our point, there are three fundamental parameters, namely:

• Radius: it requires sub-mas of spatial resolution, without forgetting that it may be wavelength dependent.

• Effective temperature: it can be determined from the angular size of the stellar source with a sufficient S/N ratio spectral energy distribution curve.

• Mass: it can be determined from dynamical masses measured thanks to precise orbital data with radial velocity measurements.

Other fundamental parameters can also be determined:

• Distance: thanks to parallactic measurements of stellar distances which can calibrate stellar luminosities.

• Temperature structure: from precise limb-darkening measurements. It requires large baselines in order to obtain data points in the 2d or 3d lobes of the visibility function.

A nice example of fundamental parameters determination is the work done by Mérand *et al.* (2011) on the eclipsing binary δ Velorum. From the modeling of the primary and secondary components of the δ Vel A eclipsing pair, they have derived their fundamental parameters with a typical accuracy of 1%. They found that they have similar masses, i.e. 2.43 $\pm$ 0.02 $M_\odot$ and 2.27 $\pm$ 0.02 $M_\odot$. The physical parameters of the tertiary component (δ Vel B) was also estimated. They obtain a parallax $\pi = 39.8 \pm 0.4$ mas for the system, in good agreement with the Hipparcos value, i.e. $\pi_{Hip} = 40.5 \pm 0.4$ mas. Zavala *et al.* (2010) have observed the Algol triple system with the NPOI interferometer and have produced, for the first time, images resolving all three components. They have separated the tertiary component from the binary and have simultaneously resolved the eclipsing binary pair, which represents the nearest and brightest eclipsing binary in the sky. On the same system, Borkovits *et al.* (2010) carried out interferometric observations both in the optical/near-infrared and in the radio regime. The optical interferometric observations were done with the CHARA array in the K_s band and they were able to test the Kozai resonance/cycles, see Kozai (1962) for more details, by determining the mutual inclination of this triple system, i.e. i=95^o $\pm$ 3^o. Another interesting work was done by Bruntt *et al.* (2010) who was able, using the CHARA/FLUOR and VLTI/NACO instruments to determine the radius and T_{eff} of the binary (ro)Ap star β CrB. This was also a way to calibrate the T_{eff} scale for Ap stars which is very helpful to constrain asteroseismic models. Another example of asteroseismic constraints thanks to interferometric measurements of multiple systems is the work done by Kervella *et al.* (2008) who were able to infer the radii and the evolutionary status of the 61 Cyg A & B K5V and K7V stars from CHARA/FLUOR data. These new radii were able to constrain efficiently the physical parameters adopted for the modeling of both stars, allowing them to predict asteroseismic frequencies (namely $\delta\ \nu_{n,l}$ & $\Delta\ \nu_{n,l}$) based on their best-fit models. Moreover, their CESAM2k, see Morel (1997), evolutionary models indicate an age around 6 Gyr and are compatible with small values of the mixing length parameter.

Interferometers were recently used to determine very precise angular diameters and T_{eff} of exoplanet host stars following the work done by Baines *et al.* (2008) and Baines *et al.* (2009) whereas Duvert *et al.* (2010) were able to detect a 5-mag fainter companion at a distance of 4 R_* around HD 59717 with VLTI/AMBER using the phase closure nulling technique. They found that errors on the secondary measurements are mainly due to the uncertainty in the flux ratio between both components rather then from the interferometric data. Finally, Absil *et al.* (2010) have carried out a deep near-infrared interferometric search for low mass companions around β Pictoris. Their results exclude the presence of brown dwarfs with m $>$ 20 M_{Jup} (resp. 47 M_{Jup}) at a 50% (resp. 90%) completeness level within the few nearby AU (2-60 mas). They also exclude the presence of companions with K band contrast $<5 \times 10^{-3}$ and finally their best data fit was obtained for a binary model at 14.4 mas from β Pic with a contrast of 1.8×10^{-3}.

4. Model fitting

Spectroscopic and photometric techniques are usually used to constrain various models but since they are providing spatially integrated observables, the solution or "best model" obtained is very often not unique since different geometrical models can produce identical spectroscopic and photometric observables. Thanks to interferometry and more especially to spectrally resolved interferometry, see Mourard *et al.* (2009), it is possible to overcome this degeneracy and put very strong constraints on modern modeling. In the following, I will illustrate how models can be constrained by interferometric measurements for the three well known binaries: ζ Tau, δ Sco and γ^2 Vel.

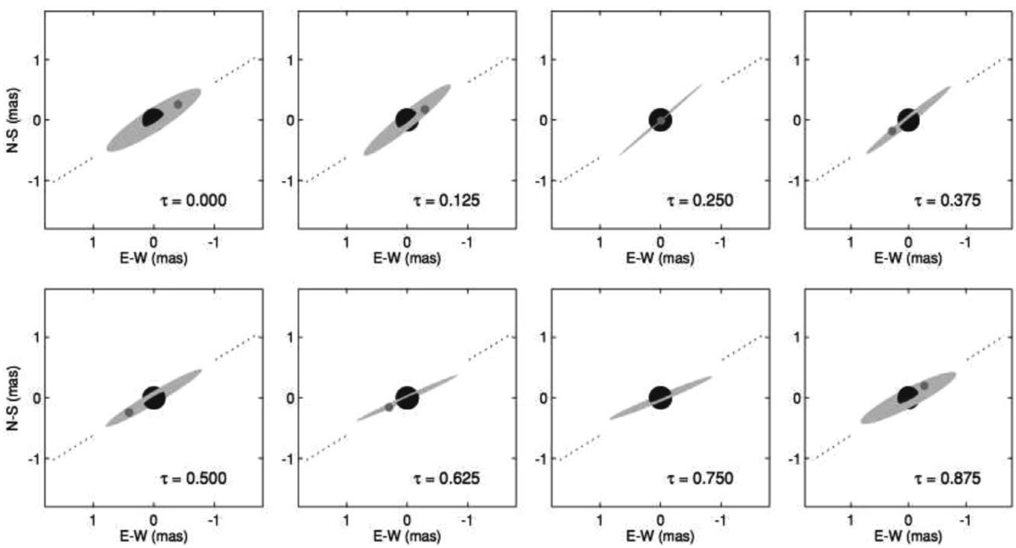

Figure 2. Cartoon depiction of the disk precession variations around ζ Tau as seen in the sky from Schaefer *et al.* (2010)

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4.1. ζ *Tau*

This binary Be star was observed by Gies *et al.* (2007) with the CHARA interferometer in the K-band. The size of the circumstellar disk, nearly edge-on, was found to be smaller than in the Hα line which is mainly due to a larger Hα opacity and a relatively larger neutral H fraction with increasing disk radius. They were able to estimate the density distribution as a function of the stellar radius and Gies *et al.* (2007) found that the "n" parameter describing the density distribution "slope", i.e. $\rho(r) = \rho_0[\frac{R_*}{r}]^n$, was smaller in binaries with smaller semimajor axies. This was direct evidence that binary companions do influence the disk properties. An asymmetry was also detected by Schaefer *et al.* (2010) with the CHARA/MIRC interferometer. They have observed a change in the position angle of the disk over time. Moreover a correlation between the position angle and the V/R phase of the Hα emission line variations suggests that the tilt of the disk around ζ Tau is precessing. They have also measured an asymmetry in the light distribution of the disk that roughly corresponds to the expected location of the density enhancement of the spiral oscillation model. Meilland *et al.* (2009) observed this star with the VLTI/MIDI instrument between 8 and 12 μm and found that the size of the disk does not vary strongly with wavelength between 8-12 μm which can be due to a disk truncation by the companion. Finally a global 3D and NETL model of ζ Tau was done by Carciofi *et al.* (2009) using the HDUST code. This model, based on a 2D global disk oscillation that is propagating within the equatorial disk, was in agreement with simultaneous VLTI/AMBER data and V/R variations in the Hα and Brγ spectral lines.

4.2. δ *Sco*

δ Sco is also a binary Be star already observed by Millan-Gabet *et al.* (2010) in 2007 with CHARA and resolved in the H continuum, Brγ, HeI and Hα lines. This is an interesting system since the companion passage at periastron is so close that tidal effects have strong effects on the formation/dissipation of the circumstellar disk around the primary. Since the rediscovery of its binarity in 1974, δ Sco has been observed several times using speckle-interferometry, mainly published in McAlister & Harkopft (1988). New speckle-interferometric measurements allowed Hartkopf *et al.* (1996) to derive more accurate and significantly different parameters. Using the same dataset complemented by radial velocity measurements close to the 2000 periastron, Miroshnichenko *et al.* (2003) refined the previous analysis. Tango *et al.* (2009) have used the same dataset but with a more consistent model-fitting algorithm from Pourbaix (1998) to estimate the orbit. One of the most recent analyses of δ Sco orbit was done by Tycner *et al.* (2011) using 96 measurements from the Navy Prototype Optical Interferometer (NPOI). Finally, Meilland *et al.* (2011) have obtained new VLTI/AMBER and CHARA/VEGA data and conclude that the next periastron passage should take place around July 5, 2011 ($\pm$ 4 days). They also found that the rotation appears to be Keplerian, with an inner boundary (photosphere/disk interface) rotating at the critical velocity. The expansion velocity within the circumstellar equatorial disk was found to be negligible and considering an outburst scenario, should be on the order of 0.2 kms^{-1}. With the measured vsini of 175 kms^{-1} and the measured inclination angle of 30.2 ± 0.7^o, the star rotates at about 70% of its critical velocity. This could indicate that the stellar rotation is not the main process driving the ejection of matter from the stellar surface. However, taking into account possible underestimation of the vsini due to gravity darkening, see Townsend *et al.* (2004), the star may rotate faster, up to 0.9 of its critical velocity.

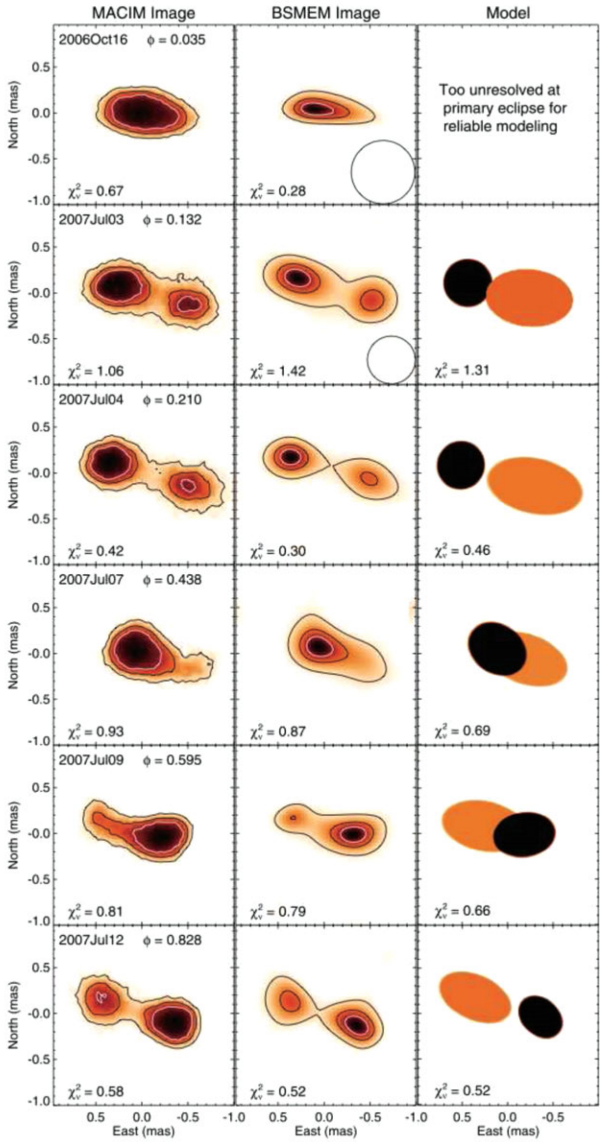

Figure 3. Reconstructed images in the H band and two-component models of β Lyrae with the CHARA/MIRC instrument from Zhao *et al.* (2008) .

4.3. γ^2 *Vel*

γ^2 Velorum is an interacting binary with a primary Wolf-Rayet star and an O type companion. This system was observed by Millour *et al.* (2007) with the VLTI/AMBER and by North *et al.* (2007) with the SUSI interferometer. Millour *et al.* (2007) using a relatively restrained data set have set tight constraints on the geometrical parameters of the γ^2 Velorum orbit. A nice example of the constraints brought by interferometry is the work done by Millour *et al.* (2007) where they have drastically reduced the error box derived from the classical radial velocity method by using an interferometric fit to retrieve the geometrical parameters of the binary star. Moreover, the smaller separation measured by interferometry means that the distance of the system must be reevaluated to 368 pc, in agreement with recent spectrophotometric estimates, but significantly larger than the Hipparcos value of 258 pc.

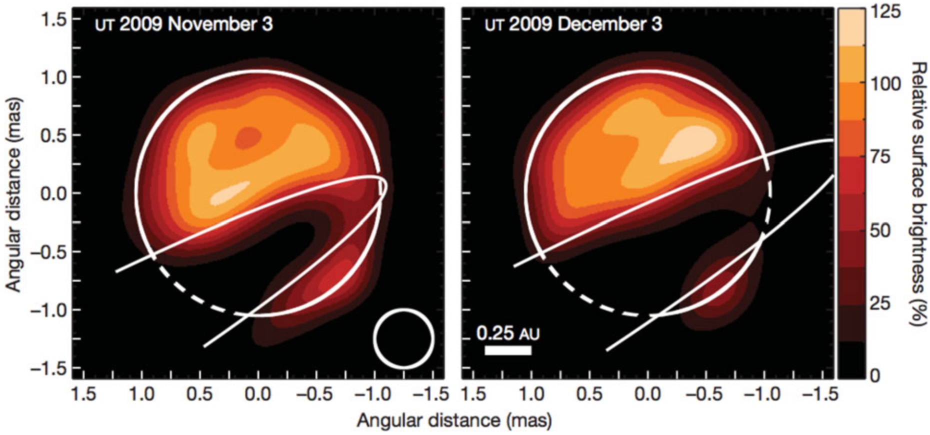

Figure 4. Synthesized images from the 2009 observations of the ϵ Aurigae with the CHARA/MIRC instrument from Kloppenborg *et al.* (2010).

5. Image reconstruction

Nowadays, it is not only possible to constrain "ad-hoc" or more physical models using interferometric data but it is also possible to directly reconstruct images without any a-priori model. This is only possible with interferometers with at least 3 telescopes in order to recover the true phase of the object onto the skyplane which is blurred by the atmosphere with only 2 telescopes. This phase can be determined thanks to the "closure phase" technique, see for instance Roddier (1986), which is the case of the CHARA/MIRC (combining up to 6 telescopes), the VLTI/AMBER (up to 3 telescopes) and the CHARA/VEGA (up to 4 telescopes) instruments. A very spectacular example is the direct image reconstruction in the H band of the interacting binary system β Lyrae done by Zhao *et al.* (2008) with the CHARA/MIRC instruments. They were able to reconstruct the image of the binary system within a few mas but also to follow its time evolution (see Fig. 3). Last but not least, another very spectacular example is the image reconstruction of the transiting disk in the ϵ Aurigae system again with the powerful CHARA/MIRC interferometer by Kloppenborg *et al.* (2010). ϵ Aur is a visually bright, eclipsing binary star system with a period of 27.1 years. Using direct imaging of the system they have demonstrated the validity of the disk model for the previously unseen companion. The elliptical appearance of the disk seems to be more consistent with a model of a tilted thin disk rather than one of a thick disk seen edge on. With these images and a simple model, they were able to estimate the dimensions and masses of the components in the system (See Fig. 4). An animation of the disk passage in front of the stellar disk obtained from the reconstructed images can be seen on YouTube†.

6. Conclusion

It is clear that interferometry in the visible and infrared is now a mature technique. Direct images are possible and spatial and spectral resolution are available with instru-

† http://www.youtube.com/watch?v=LfKMmCkV1xE

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ments using spectrally resolved observations such as the CHARA/VEGA interferometer. The main drawback is certainly the limited magnitude of the current interferometers, i.e. around 7 in K with the VLTI/AMBER instrument and around the same magnitude in the visible/infrared for the CHARA interferometer. The VLTI is a general user ESO interferometer open to the general community through call for proposals‡ whereas CHARA instruments¶ are generally accessible via collaborations with the PI of a focal instrument.

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‡ `http://www.eso.org/sci/observing/phase1/proposalsopen.html`
¶ `http://www.chara.gsu.edu/CHARA/`

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