Interferometric studies of multiple stars

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Summary. Long baseline optical and infrared interferometry (LBI) has been immensely successful in resolving spectroscopic binaries in order to enable the determination of stellar masses and luminosities. However, the technique has been applied to only a very few cases of higher multiplicity, namely triple stars. I will discuss in the following a specific case, η Virginis, while I provide other references on the technique instead of repeating them here.

1 If you have been thinking of using LBI...

Long baseline interferometry (LBI) is a special technique to achieve the highest spatial resolution at the expense of being able to image complex structure with high dynamic range. Therefore, single and multiple stars have been the main target over the past couple of decades, with astrophysically important results [5].

The observations of simple targets such as single and multiple stars are no exception to the rule that in general, interferometry has to be combined with other techniques since it probes only limited spatial frequencies. If one considers LBI for a target, one should therefore consult a checklist [4] in order assess the feasibility of the observations. Most importantly, the expected target size needs to be known, and matched to the available baselines. In addition, the homepage of the European Southern Observatory (ESO) provides tools such as VisCalc and CalVin (http://www.eso.org/observing/etc/index.html) supporting observations with the Very Large Telescope Interferometer (VLTI).

As the number of stations in the interferometric arrays has increased, albeit modestly and slowly, interferometers may now be considered as telescopes and no longer as a sort of ruler. In the following I will point out the important but perhaps less obvious consequences of this classification.

1.1 Imaging, dynamic range, and fidelity

Naturally, imaging is what a telescope should be able to perform, and interferometers are no exception [2]. However, those arrays which have a sufficient number of elements are capable to produce images of only simple structures having to do with the limited sampling of the aperture plane. Just as in the radio where interferometric imaging techniques have been pioneered, the dynamic range, i.e. the ratio of the peak map intensity to the lowest believable contour, is a function of the quality of the data, including calibration. However, fidelity to complex structures is only a function of aperture coverage, and can be limited even if the dynamic range is high.

As of 2005, images from LBI are usually made for public relations, as structural parameters are always obtained by fitting the appropriate models directly to the visibility (and other complementary) data.

1.2 Photometric field of view

In terms of the photometric field of view (FOV), three classes can be identified, a wide field belonging to Fizeau-type combiners, intermediate belonging to the Michelson type, and narrow belonging to the Michelson type but using single-mode fibers for improved data quality. The Large Binocular Telescope's LINC-NIRVANA beam combiner belongs to the first class, while VLTI's MIDI and AMBER beam combiners belong to the second and third class, respectively. MIDI's FOV is about 2 arcseconds using the UTs, while AMBER's FOV is only about 60 mas using the UTs.

1.3 Interferometric field of view

As the observable of an interferometer is the visibility, the amplitude of which is related to the contrast of the fringes in the interference pattern, or fringe packet, and as the latter is a superposition of the fringe packets across the (photometric) field of view, the interferometer is insensitive to directions falling outside the central fringe packet located at the phase center of the pointing direction. The area over which photons contribute to the central fringe packet is called the interferometric field of view. It is roughly equal to $R\lambda/B$, where R is the spectral resolution, and λ/B is the fringe spacing (B being the length of the projected baseline).

The width of the fringe packet is inversely proportional to the bandwidth of the received radiation. In Fig.1 one can see the two well separated fringe packets produced by the two components of the binary star 12 Persei. The same star was observed by the Mark III interferometer in a narrow channel centered at 800 nm, and one can see from the typical variation of the visibility amplitude during the night that in this case the fringe packets overlapped (see Fig.2).

If a component from a multiple star systems falls *outside* the interferometric but *inside* the photometric field of view, the visibility amplitude will be decreased by a factor $f = 1 + 10^{-\Delta m/2.5}$, where Δm is the magnitude difference between that component and the combination of all others.

1.4 Broadband aperture synthesis

Various interferometers are also acting as spectrometers, which is to say that the visibility is measured in several, and in some cases many hundreds of wavelength channels. If these cover significant fractions of the spectrum, so will the aperture coverage be increased due to the spatial frequency being the ratio of baseline length over wavelength. However, the increase in aperture coverage is offset in a way due to the fact that the target structure most likely will vary with wavelength, thus prohibiting the simple combination of all visibility data to obtain an image of the target. Also, the interpretation of the visibility spectrum is complicated by the changing spatial resolution along the wavelength axis.

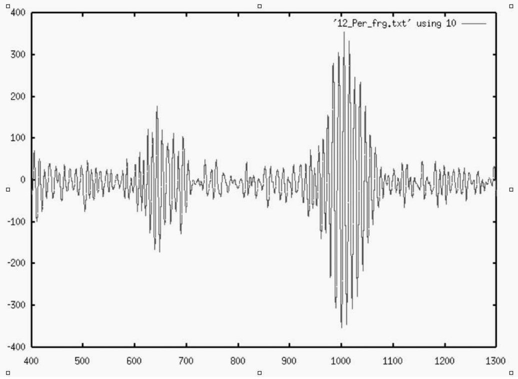

Fig. 1. The two fringe packets produced by the 40 mas-separated components of 12 Persei, as observed on Oct 9, 2001, with the 330 m baseline of the CHARA Array in the K'-band.

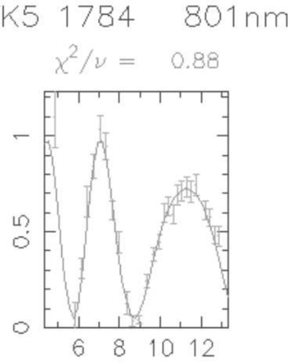

Fig. 2. Visibility amplitude of 12 Persei observed October 8, 1992, at 50 mas separation on a 12 m baseline of the Mark III interferometer at 800 nm, bandwidth of 22 nm.

2 Modeling of interferometric observations of η Virginis

The triple star η Virginis was the first triple system to be fully resolved by LBI, and these observations at the same time constituted the first successful operation of a six-station array [3].

2.1 Visibility function and data

The first epoch (of 27) observations are shown in Fig.3, more specifically the location in the aperture plane (also called *uv*-plane) of the measurements taken by the 11 baselines of the NPOI [1] during the night. The longest NPOI baselines resolved the close pair in this triple system, while the shorter baselines were sensitive to the wide separation.

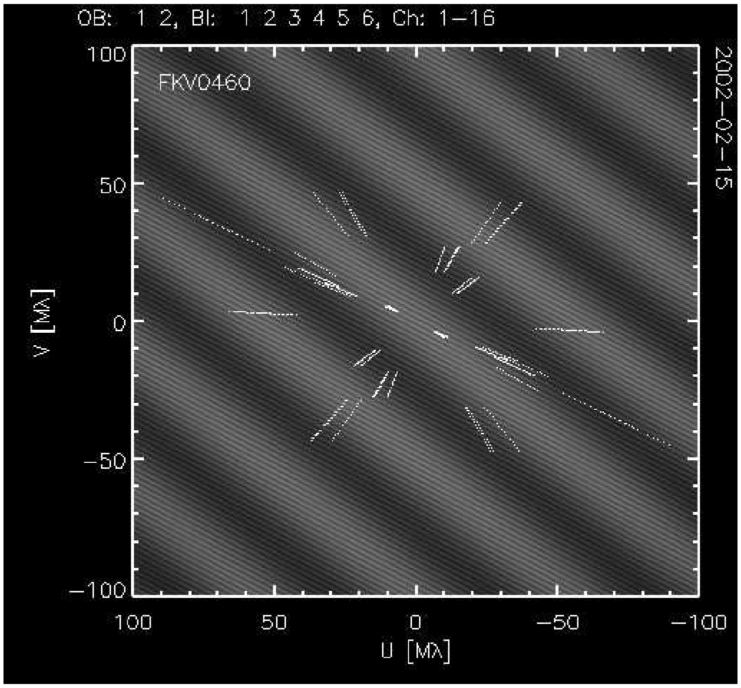

Fig. 3. Aperture coverage provided by the NPOI six-station array for the observations of η Virginis on February 15, 2002. The grey-scale image corresponds to the amplitude of the squared visibility function predicted by a model of the triple system and fitted to the data. One can discern two systems of stripes corresponding to the two binary components in this hierarchical system, with the narrow stripes due to the larger spacing.

2.2 Hierarchical model format

As we are for the time being only interested in hierarchical systems, which cover most of the cases of higher multiplicity anyway, we developed the format shown below to specify component and orbital parameters. For each component in a multiple system, e.g. A, B, C for the components in a triple system, we specify the stellar parameters which can be fitted to the data, including radial velocities if available. In a triple system, the binary components to be specified can then be A-B and AB-C, or B-C, A-BC.

```
name(0)          ='A'                 component(0)    ='A-B'
wmc(0)           ='Aa'                method(0)       =1
mode(0)          =1                   semimajoraxis(0)=7.36
mass(0)          =2.68                inclination(0)  =45.5
diameter(0)      =0.46                ascendingnode(0)=129.5
magnitudes(*,0)  =[4.2,4.2]           eccentricity(0) =0.244
```

```
;
name(1)         ='B'
wmc(1)          ='Ab'
mode(1)         =1
mass(1)         =2.04
diameter(1)     =0.21
magnitudes(*,1) =[6.0,6.0]
;
name(2)         ='C'
wmc(2)          ='B'
mode(2)         =1
mass(2)         =1.66
diameter(2)     =0.15
magnitudes(*,2) =[6.5,6.3]
```

```
periastron(0)   =196.9
epoch(0)        =2452321.4
period(0)       =71.7916

component(1)    ='AB-C'
method(1)       =1
semimajoraxis(1)=133.7
inclination(1)  =50.6
ascendingnode(1)=170.8
eccentricity(1) =0.087
periastron(1)   =2.3
epoch(1)        =2447896.2
period(1)       =4774.0
```

Diameters and magnitude differences can be constrained by the interferometry; individual magnitudes are then constrained by the combined magnitudes known for the system. Magnitudes and semi-major axes can be used to predict the motion of the photocenter if the close pair should not be resolved by the interferometer. The masses are constrained if radial velocity data are added to the interferometric data (discussed below).

2.3 Astrometric mass ratio

Both pairs in the triple system η Virginis have been resolved and the orbital motion measured by NPOI [3]. Since the tertiary component is only slowly moving and its motion can be modeled using the extensive speckle interferometric data, it provides a reference position for the component motions in the close pair. This enabled the measurement of the component mass ratio in the close pair, providing an estimate independent of the one derived by the semi-amplitudes of the radial velocity curves.

2.4 Combined modeling

Stellar masses are model parameters since we fit the model to a combination of spectroscopic and interferometric data, allowing to make the fit more robust and obtain astrophysically relevant parameters more directly. In the case of η Virginis, the close pair is a double-lined spectroscopic binary, allowing to measure masses of and distance to this pair. Therefore, even without the radial velocity curve of the tertiary, its mass can be determined also.

We implemented combined modeling with the safeguards provided by the Singular-Value-Decomposition method [6] against inadvertently selecting unconstrained parameters for a fit, and use the Levenberg-Marquardt implementation of non-linear least-squares fitting [6]. Relative weights of the data sets are set to normalize the reduced χ^2 for them individually before combination.

3 ...now is a good time to do it.

The VLTI operated by ESO is the first to offer LBI in service mode, which enables astronomers to have observations executed in absentia and raw data delivered to them meeting certain quality contol criteria. Software for the data reduction is available, e.g. through JMMC (http://mariotti.ujf-grenoble.fr/) and NOVA (http://www.strw.leidenuniv.nl/ nevec/index.html).

References

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