Spectroscopically and Spatially Resolving the Components of Close Binary Stars
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Using Speckle Interferometry to Resolve Binary Stars

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Abstract. Speckle interferometry has proven to be a powerful tool to detect sub-arcsecond binaries and measure their parameters. However, due to the sophisticated methods required to reduce the data, not very many astronomers know how to use it. In this contribution, I describe the basic methods used to reconstruct modulus and phase of the Fourier transformed high-resolution image from speckle data. I will also show some example data of binary stars, and demonstrate why the simple structure of the Fourier transform of binary star images makes them ideal targets for speckle-interferometry, allowing to detect binaries with separations at and sometimes even below the diffraction limit of the telescope.

1. Introduction

In order to spatially resolve and study close binary stars, it is in most cases necessary to achieve high angular resolution. However, direct imaging with ground based telescopes is limited by the turbulence of the atmosphere, which blurs the images of point sources to a broad peak with a diameter of the order of $1''$ (see Fig. 1, left panel), so all high-resolution information is lost.

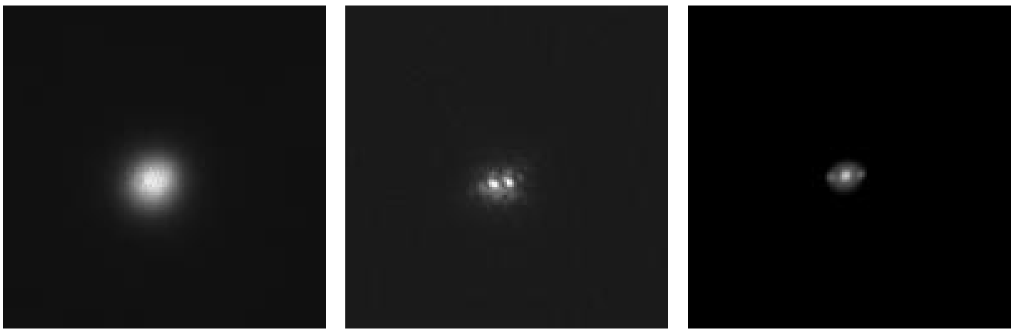

Figure 1. Left: A long (125 sec) exposure of a star. Middle: The same star in an image exposed for only 0.5 sec. Right: An image of the star obtained with the Shift-And-Add method, using about 125 input images. The field-of-view of the images is $6.4''$.

Fortunately, with sufficiently short integration times, the turbulent atmosphere is "frozen", so we can obtain images that retain the high-resolution information. Sufficiently short means shorter than the coherence time of the atmosphere, which is of the order of a few tenths of a second. The middle panel of Fig. 1 shows an example. The image is still distorted by the inhomogeneous atmosphere, which causes the characteristic specks of light that gave the method its name. (It is called Speckle-*Interferometry* because the short-exposure images are interferograms of the atmosphere.) The signal-to-noise ratio of these images is very poor, so that detection of even moderately faint companions is difficult or impossible.

The way to overcome this problem is to take many images, usually several hundreds or thousands, and combine them in a way that preserves the small structures.

2. The Shift-And-Add Method

The easiest way to combine images without destroying the high-resolution information is the so-called Shift-And-Add method. Here, one searches for the brightest pixel in each image, shifts the image so that this pixel is in the center, and then adds the shifted images together. An example for the result is shown in the right-hand panel of Fig. 1. There are two major disadvantages when using this method for binary stars: First, if the two components have similar brightness, the brightest pixel is not always on the primary. Shift-And-Add images of these systems look like a triple star with three components on a straight line. Second, only the brightest speckle contributes to the central peak, the rest of the light creates a halo around the star, which makes it impossible to obtain useful photometric information from Shift-And-Add images of close binaries. Other implementations are possible, e.g. use the center of light instead of the brightest pixel, but the problem of the halo remains.

3. Powerspectrum Analysis

In order to understand the way speckle-interferometry overcomes these limitations, we have to examine what happens to the light on the way to the telescope. The image $I(x)$ we record on our detector is the convolution of the true brightness distribution of the object $O(x)$ with the so-called Point Spread Function (PSF) $P(x)$:

$$I(x) = \int O(x') \cdot P(x - x') \, \mathrm{d}x' \,.$$

(Note that x is a position in the two-dimensional image plane). A Fourier-transform turns this relation into a simple product:

$$\tilde{I}(u) = \tilde{O}(u) \cdot \tilde{P}(u) \,.$$

The simple idea to divide $\tilde{I}(u)$ by $\tilde{P}(u)$ to get $\tilde{O}(u)$ is not feasible because $\tilde{P}(u)$ may contain zeroes, $\tilde{I}(u)$ is noisy, and because we usually do not know $\tilde{P}(u)$.

Labeyrie (1970) proposed to use the power spectrum of the image $|\tilde{I}(u)|^2$ and average the power spectra of many images. This quantity is much less problematic with regard to zeroes and noise, and it varies much slower over time. Thus, we can observe an unresolved star[1] shortly before or after the science target. Since the brightness distribution of an unresolved star is a delta-function, an image of it is simply the PSF:

$$I_{\mathrm{ref}}(x) = \int \delta(x') \cdot P(x - x')\, \mathrm{d}x' = P(x)\,.$$

From the power spectra of the images of science object and reference star we obtain the power spectrum of the brightness distribution of the science target:

$$|\tilde{O}(u)|^2 = \frac{< |\tilde{I}_{\mathrm{obj}}(u)|^2 >}{< |\tilde{I}_{\mathrm{ref}}(u)|^2 >}\,,$$

where $< \ldots >$ denotes averaging over several images.

The Fourier-transform of the brightness distribution $\tilde{O}(u)$ is called the complex visibility. From the power spectrum, we can obtain only its modulus $|\tilde{O}(u)|$, which is usually called the visibility. However, the modulus contains almost every piece of information we want to know about a binary. One can see in the examples in Fig. 2 that the direction of the stripe pattern gives us the position angle of the binary, the distance of the stripes is inversely proportional to the binary separation, and the contrast of the stripes gives the flux ratio of the components.[2]

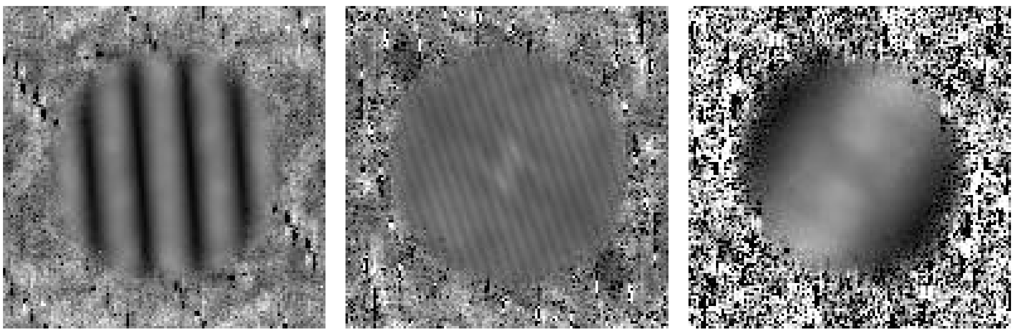

Figure 2. Examples of visibilities of binary stars. The star to the left is the same as in Fig. 1, it has a separation of $0.3''$, a position angle of $5°$, and a flux ratio of 0.85. The binary in the middle panel has $1.4''$, $200°$, and 0.07, the one to the right has $0.08''$, $327°$, and 0.7, so its separation is about half the diffraction limit of the telescope used ($\lambda/D = 0.13''$). North is left in the images. The visibility is limited to a circular region because of the diffraction limit of the telescope. We cannot recover structures at frequencies higher than the cut-off, thus we see only noise there.

[1]Finding such a star is not trivial, of course, since many stars are binaries.

[2]The program used at the conference to demonstrate how the binary parameters influence the visibility is available from the author.

4. Speckle-Holography

The visibility of a binary star is symmetrical, even if the components have different brightnesses. Thus, we can measure the position angle only with an 180° ambiguity. To overcome this limitation, we need the full complex visibility, modulus and phase. One way to get this is Speckle-Holography.[3]

The method requires a reference star close to the science target, closer than $\sim 20''$. Within this region (the so-called isoplanatic patch), the PSF of science target and reference star are almost identical, so if the reference star is in the field-of-view, we immediately have the PSF of each individual frame. The part of the image that contains the reference is then used to recover the object brightness distribution:

$$\tilde{I}(u)\,\tilde{I}^*_{\rm ref}(u) = \tilde{O}(u)\,\tilde{I}_{\rm ref}(u)\,\tilde{I}^*_{\rm ref}(u) = \tilde{O}(u)\,|\tilde{I}_{\rm ref}(u)|^2$$

$$\Longrightarrow \quad \tilde{O}(u) = \frac{\tilde{I}(u)\,\tilde{I}^*_{\rm ref}(u)}{|\tilde{I}_{\rm ref}(u)|^2}\,.$$

To improve the signal-to-noise ratio, many hundreds of images are averaged, similar to the standard Speckle method.

The disadvantage of Speckle-Holography is obvious – only a few scientifically interesting objects are close enough to a suitable reference star. The most notable target is the core of the Orion Nebula Cluster, the famous Trapezium, where the bright OB stars can serve as reference stars. Fig. 4. shows a mosaic of this region obtained with Speckle-Holography (Petr et al. 1998).

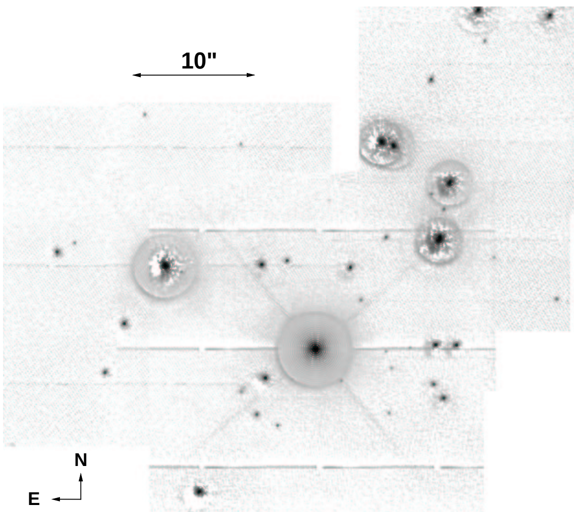

Figure 3. Mosaic of the Trapezium in the Orion Nebula Cluster, constructed from diffraction-limited images obtained using Speckle-Holography (Petr et al. 1998).

[3]The name is based on the idea that it allows to reconstruct the whole image, modulus and phase. It has no connection with 3-dimensional imaging.

5. Knox-Thompson

Another method to reconstruct the phase of the complex visibility was proposed by Knox & Thompson (1974). This method uses the cross-spectrum of the image, i.e. the product of two different points in frequency space:

$$\begin{aligned} < \tilde{I}(u)\,\tilde{I}^*(v) > &= |\tilde{I}(u)|\,e^{i\varphi(u)} \cdot |\tilde{I}(v)|\,e^{-i\varphi(v)} \\ &= |\tilde{I}(u)|\,|\tilde{I}(v)|\,e^{i(\varphi_{\rm obj}(u)-\varphi_{\rm obj}(v)+\varphi_{\rm PSF}(u)-\varphi_{\rm PSF}(v))}\,, \end{aligned}$$

where $\varphi_{\rm obj}$ is the true phase of the object, and $\varphi_{\rm PSF}$ are the distortions introduced by the atmosphere. For small differences in frequency $|u-v|$, the phase differences are constant over time, so we can use the reference star to get the phase difference of the distortions:

$$\varphi_{\rm PSF}(u) - \varphi_{\rm PSF}(v) = {\rm Phase}(< \tilde{I}_{\rm ref}(u)\,\tilde{I}^*_{\rm ref}(v) >)$$

And therefore

$$\varphi_{\rm obj}(u) - \varphi_{\rm obj}(v) = {\rm Phase}(< \tilde{I}_{\rm obj}(u)\,\tilde{I}^*_{\rm obj}(v) >) - {\rm Phase}(< \tilde{I}_{\rm ref}(u)\,\tilde{I}^*_{\rm ref}(v) >).$$

With these phase differences, we can iteratively reconstruct the phase at all frequencies, starting from frequency zero. Since the image is real, its Fourier transform at zero (which is simply the integral over the image) is also real and its phase is therefore zero. The phase at frequency one is then derived from $< \tilde{I}(1)\,\tilde{I}^*(0) >$ and so on. Figure 4 shows the phases reconstructed this way for the same binaries as in Fig. 2.

Figure 4. Phases reconstructed using the Knox-Thompson-method of the same binaries as in Fig. 2. The phase of a binary shows characteristic jumps at the position of the minima of the visibility.

6. Bispectrum

Lohmann and Weigelt developed a different method to reconstruct the phase (Weigelt 1977, Lohmann et al. 1983), called Speckle-masking or Bispectrum-method. The Bispectrum is the product of three points in the Fourier-transformed image:

$$\tilde{B}(u,v) =< \tilde{I}(u)\,\tilde{I}(v)\,\tilde{I}^*(u+v) > .$$

The phase of this quantity is quite insensitive to atmospheric distortions, similar to the closure phase in long-baseline interferometry. This gives another way to computer the phase at frequency $u + v$:

$$\varphi(u+v) = \varphi(u) + \varphi(v) - \mathrm{Phase}(\tilde{B}(u,v)).$$

Again, we make use of the fact that the phase at frequency zero is zero. However, we need a second points to start the iteration. For this, it helps that a shift in image space corresponds to adding a linear term to the phase. Since we are not interested in the absolute position, we can set the phase at frequency one to zero. Then, we can obtain the phase at any point $u + v$ by averaging over all possible combinations of u and v where the phases have already been reconstructed:

$$\varphi(u+v) = \frac{1}{N} \sum_{u,v} \left(\varphi(u) + \varphi(v) - \mathrm{Phase}(\tilde{B}(u,v)) \right).$$

This average improves the signal-to-noise ratio compared to the Knox-Thompson-algorithm. On the downside, the Bispectrum requires more computing time, a few hours on a modern workstation for a reasonably-sized data set, while the Knox-Thompson-method takes only a few minutes.

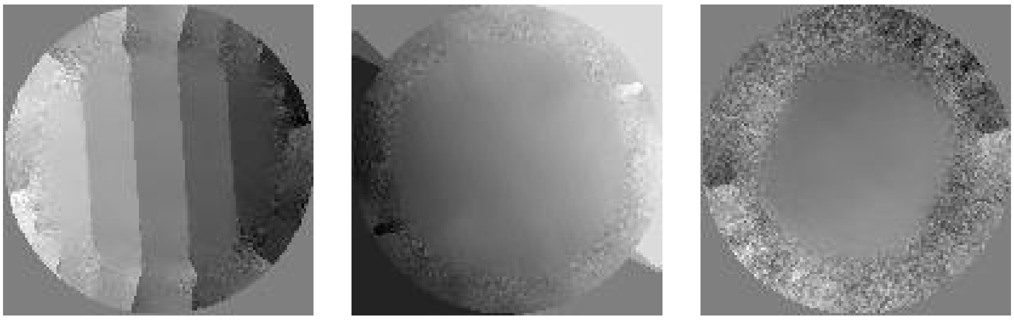

Figure 5. Phases reconstructed using the Bispectrum method of the same binaries as in Fig. 2. To save computing time, we do not reconstruct the phases in the corners of the image.

Figure 6. Images obtained by Fourier-transforming visibilities from Fig. 2 and phases from Fig. 5 back into images space.

Figure 5 shows the phases of our example binaries reconstructed from the Bispectrum, and Fig. 6 shows that we can indeed obtain images of binaries by Fourier-transforming visibility and phase. The components of the binaries with medium and large separations are clearly visible, but the close binary is hardly detectable in image space. In comparison, its extended nature is obvious in the visibility in Fig. 2. This is one of the reasons why we hardly ever compute the back-transform, but fit binary models to the complex visibility in Fourier space.

7. Limits for undetected Companions

For a binary survey, it is not only important to detect binaries and measure their parameters, but also to specify the limits for undetected companions. In Fourier space, this can be done by measuring the deviation from the visibility of a single, unresolved star, i.e. a flat power spectrum.

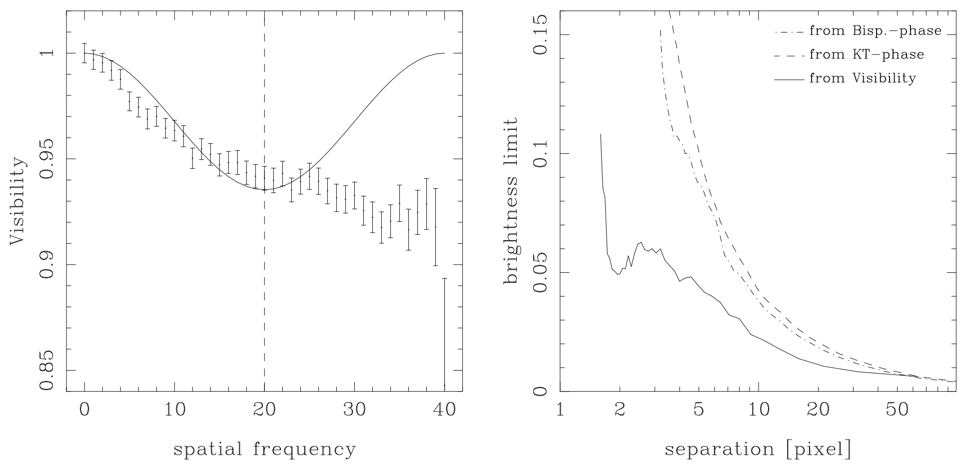

Figure 7. How to measure limits for undetected companions. Left: The measured visibility of a supposedly unresolved star, and the expected visibility of a binary that is compatible with the data at a frequency of 20. Right: The brightness limit as function of separation for this star.

Figure 7 shows the one-dimensional projection of a star we consider unresolved. The cosine curve shows the visibility function of a binary with the maximum amplitude that is still compatible with the measured visibility at a spatial frequency of 20. This maximum amplitude can be transformed into the maximum brightness of an undetected companion at the corresponding separation. Repeating this procedure for different spatial frequencies gives the maximum brightness as function of separation, shown at the right-hand side of Fig. 7. In principle, the limit also depends on the position angle, but it is usually sufficient to consider the worst case, i.e. the maximum of all brightness limits at a given separation. The phase of the star can be analyzed in a similar way, so we can obtain three different measurements from power spectrum, Knox-Thompson-, and Bispectrum-method (also shown in Fig. 7, right panel).

8. Examples

8.1. Orbital Motion: LHS 1070

LHS 1070 (also known as GJ 2005) is a nearby M5V star that is orbited by a close pair of low-mass stars, making this a triple system. We observed it using Speckle interferometry on several occasions since 1993, Fig. 8 shows three examples. The wide pair has a position angle of about 0° and causes the tight stripe pattern. The wider pattern with less contrast is due to the close pair. Its orbital motion resulted in a change of position angle from about 330° to 16°, and in separation from 0.27″ to 0.47″ (Leinert et al. 2001).

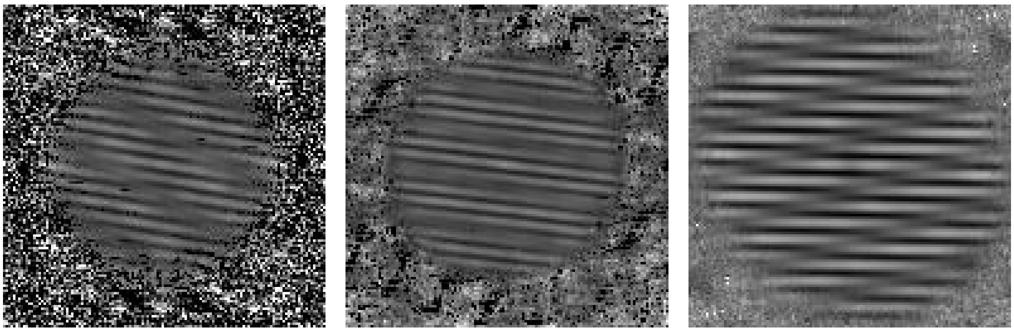

Figure 8. Visibilities of LHS 1070 in 1993, 1994, and 1996. The image to the right was taken with a different telescope, therefore the pixel scale is different.

8.2. "AO-assisted Speckle" — T Tauri S

Speckle interferometry is still useful, even in the times of adaptive optics systems. An example is T Tauri, which has a companion about 0.6″ south. Koresko (2000) discovered with the help of the Keck telescope and Speckle holography that the companion itself is a binary with a separation of only 50 mas. We observed T Tauri in February 2000 with the adaptive optics system ALFA at the 3.5m telescope on Calar Alto (Köhler et al. 2000). On the resulting images (Fig. 9), North and South components are clearly separated, but T Tauri S shows no sign of binarity. We then used T Tauri N as reference star to compute the power spectrum of T Tauri S (also shown in Fig. 9). Although there is a lot of noise caused by the truncation of the PSF and light from T Tauri N leaking into the image, the striping pattern of a binary with position angle 253° is visible.

9. Conclusions

Speckle interferometry is a well proven technique for the study of binary stars. Observations routinely reach the diffraction limit of the telescope and it is possible to detect binaries with even smaller separations. In Fourier space, the binary parameters can be determined from a large number of pixels, not just from a few pixels around the peaks in image space. Therefore, Speckle interferometry allows very precise measurements of binary parameters.

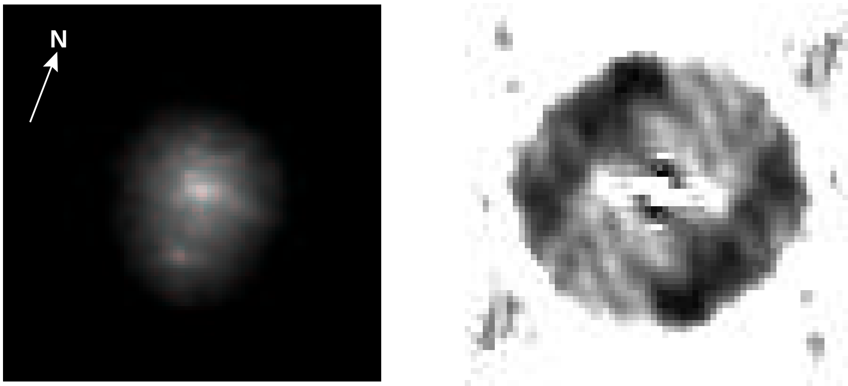

Figure 9. Left: Image of T Tauri obtained with the adaptive optics system ALFA. Right: The power spectrum of T Tauri S, computed using T Tauri N as reference star.

Speckle interferometry also has some disadvantages: it is only possible to observe bright sources (brighter than $\sim 10\,$mag in the K-band) with a relatively small dynamic range ($\Delta K \lesssim 3\,$mag). The field-of-view is limited to the region where the PSF is constant (the isoplanatic patch, diameter $\sim 40''$). In practice, the method is limited by the size of detector arrays that can be read out fast enough, which allows to cover only about $15''$. Nevertheless, there are plenty of binaries that can be observed.

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