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Imaging and Modeling of Binaries with NPOI

C.A. Hummel

US Naval Observatory, 3450 Massachusetts Avenue NW, Washington, DC 20392, USA

Abstract. This paper focuses first on ground based observations with long baseline optical interferometers of a class of binaries featuring double-lined or variable spectra. Following a short perspective on implications of this technique, we present imaging and modeling results of two double stars (ζ Orionis A and o Leonis) observed with the Navy Prototype Optical Interferometer (NPOI). Brief introductions are given on both topics, as well as an outline of current plans. Secondly, we simulate future imaging observations of stellar disks with NPOI, and elaborate on related issues of array design and wavelength coverage. We point out differences between optical interferometry and the well established technique of radio interferometry on very long baselines.

1. Introduction

In a manner of speaking, the extraordinary resolving power of modern optical long baseline interferometers is about to lead to the disappearance of the spectroscopic binary as a species. Not more than 15 years ago, an unbridgeable gap existed between the vast majority of stars exhibiting periodic line shifts as well as composite spectra and what direct imaging methods could do to *see* the companions.

These days, interferometers like COAST (The Cambridge Optical Aperture Synthesis Telescope, UK) and NPOI (The Navy Prototype Optical Interferometer, AZ) routinely produce images on scales of a few milliarcseconds, and are about to resolve the majority of the "spectroscopic" binaries. Such images have been published of Capella (Baldwin et al. 1996) and of Mizar A (Benson et al. 1997). The latter star has a long history of astronomical firsts. It was the first double star (components A and B) to be discovered by J. B. Riccioli of Bologna, Italy (and possibly even earlier by G. Galileo, see a web page by L. Ondra at `http://www.bm.cesnet.cz/~ondra/mizar/article.htm`), the first to be photographed by G. P. Bond of Harvard College Observatory in 1857, and the first spectroscopic binary (component A) measured by E. Pickering, also at Harvard. Now, a very accurate orbit of Mizar A has been published (Hummel et al. 1998), with median residuals of 70 microarcseconds.

Ground based optical interferometers feature long baselines of up to several hundreds of meters and achieve very high resolution despite atmospheric turbulence since they are designed, in effect, as adaptive telescopes. A good review of the current instrumentation can be found in Armstrong et al. (1995).

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14. ABSTRACT **The Navy Prototype Optical Interferometer is operational with three baselines of up to 38 meters, which can be combined to form a closure phase usable for obtaining images. Work is well underway to extend the baseline lengths to a maximum of 437 meters, as well as to implement a 6-way beam combiner which will enable the simultaneous operation of 15 baselines. Since NPOI records data over a wavelength range of 500 nm to 850 nm, the coverage obtained with Earth-rotation aperture synthesis rivals the aperture coverage of narrow-band multi-station radio interferometers. In order to investigate the technique of obtaining images from NPOI data, we present actual imaging results, as well as images from simulated NPOI observations of stellar surfaces and multiple stellar systems. We discuss issues including the wavelength dependence of stellar structure, as well as their variability during the observations. We also point out fundamental differences to the imaging of radio data.**					
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2. The Navy Prototype Optical Interferometer

Conceptually, the NPOI looks like the VLA (The Very Large Array, NM, a connected element radio interferometer). because of its Y-configuration of stations. Each arm in the Y is 250 m, providing baselines of up to 440 m. At optical wavelengths, this gives a resolution of better than 300 μas. There are 30 stations all together. Combined with a vacuum feed system, vacuum delay lines, six moveable siderostats featuring 35 cm clear aperture, and 32 channels covering 450 nm to 850 nm including IR capabilities, the NPOI will be a powerful research tool for multiple stellar systems and disks of stars. A thorough description can be found in Armstrong et al. (1998).

3. Imaging

The recent achievement of producing images (rather than just models) of stars has highlighted the potential of optical interferometers. A great deal of experience dealing with imaging sparse aperture interferometric data has been gathered by VLBI (Very Long Baseline Interferometry, intercontinental baselines of radio telescopes), a radio technique now routinely producing high dynamic range maps ($>$ 1000) using phase and amplitude self-calibration as well as image deconvolution algorithms. Whereas in VLBI the fundamental observables are the visibility amplitude and phase, in optical interferometry they are the squared amplitude and closure phase. Closure phases are the sum of the visibility phase between three (or more) stations. They are the only phases free of atmospheric phase noise and thus suitable for imaging provided the missing phase information is substituted with model phases. This is the essence of phase self-calibration. In addition, optical interferometers can observe very wide band passes, which can be used to fill in the aperture coverage in order to enhance the stability of the imaging process, but requires solving (or accounting) for the wavelength dependence of the source structure. Such imaging algorithms have not been developed yet.

For the images in this work, we have taken the square root of the squared visibility amplitude, and assigned the one closure phase (three station observations) to one of the baselines while setting the other two baseline phases identical to zero. The data was then imaged using the AIPS (Astronomical Image Processing System) software commonly used for radio data. Typically, the model converged in about five iterations.

4. Modeling

In order to obtain astrophysical parameters of the stellar systems, modeling is the best and most robust technique if the source structure can be described with just a few well defined structural elements (disks, uniform or limb darkened, possibly with spots, etc.). Data from different techniques (e.g., interferometry, spectroscopy, photometry) can be combined to better constrain the model parameters. We have developed a hierarchical model format including physical parameters, like masses and effective temperatures, for fitting the data. In addition, model atmosphere spectra are used to obtain fluxes and limb darkening coefficients which are integrated over the NPOI channel passbands.

In the case of binaries, orbital elements are part of the set of model parameters, and can be fit either directly to the visibility data if the orbital period is short, or to the relative positions determined either from interferometry or by other means (e.g., speckle).

5. Close binaries

Continuing a program initiated at the Mark III interferometer (e.g., Hummel et al. 1995), observations of spectroscopic binaries have been made with NPOI in order to resolve the components and map their relative orbits. In addition to measuring the relative component positions, the NPOI data also allow us to determine their magnitude difference and thus the individual components' brightnesses.

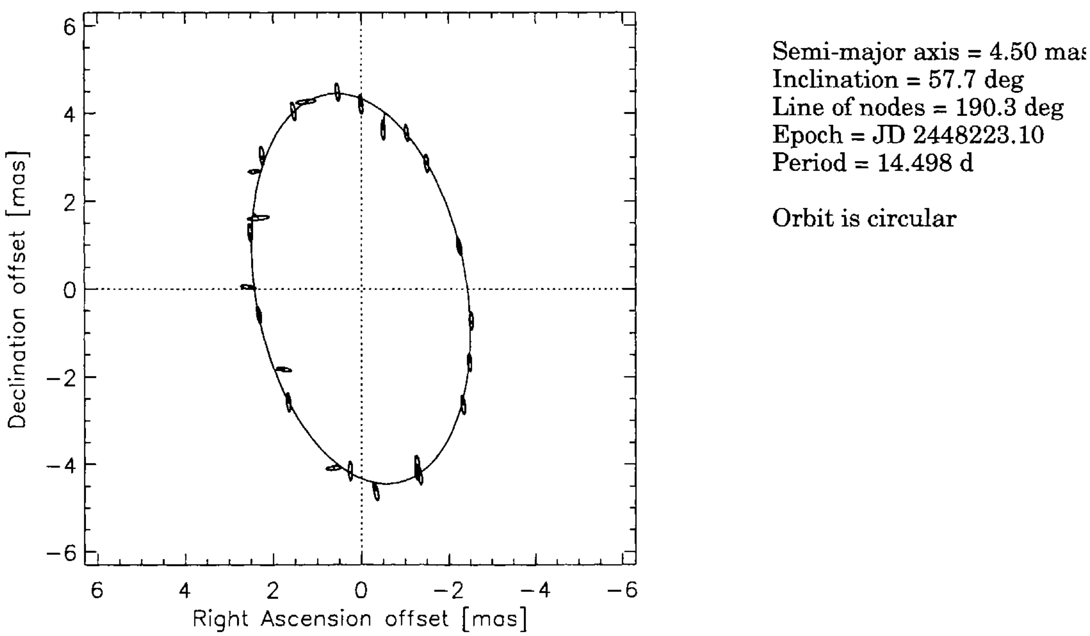

Figure 1. The apparent orbit and preliminary elements of *o* Leonis with data from NPOI and the Mark III.

6. Wide binaries

Binaries with component separations between several tens of mas and about 150 mas are observable both with NPOI and speckle interferometry. As the latter method does not provide good relative photometry of the components, NPOI photometry in the V and I bands adds important information for deriving component luminosities. We have selected from the WDS (The Washington Double Star Catalog, maintained at the US Naval Observatory) systems with current separations of less than 200 mas, and are observing some of them routinely. We present here maps of the bright O9.7 supergiant ζ Orionis A, in which we found a companion about 2 magnitudes fainter than the primary. The orbital motion can clearly be seen and a preliminary orbit suggests a period of about 7.5 years.

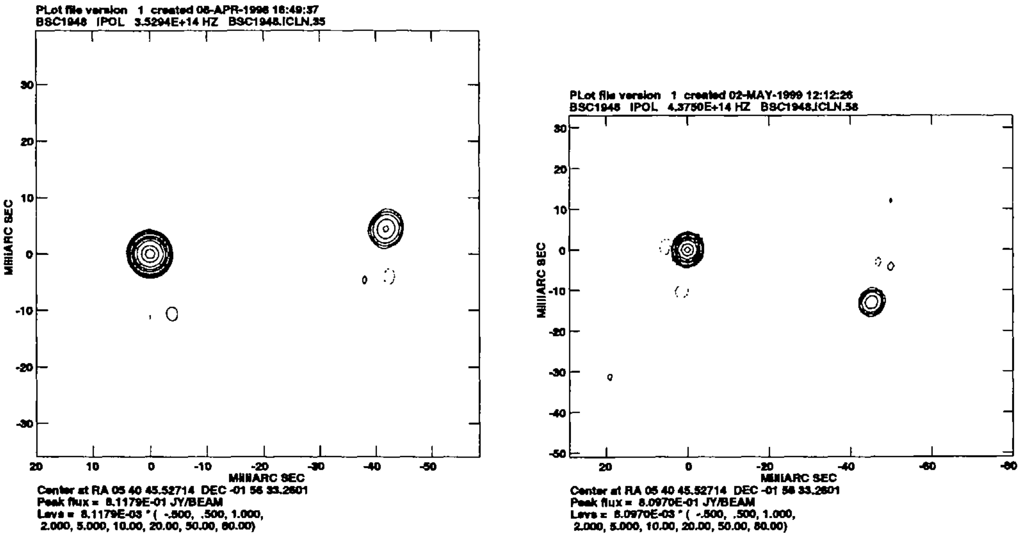

Figure 2. Maps of ζ Orionis A for February 1998 and 1999.

7. Stellar masses and luminosities

If one selects from the catalog of Batten et al. (1989) all spectroscopic binaries (with orbits) brighter than $V = 6$, north of $-10°$, and with estimated semi-major axes between 1 mas and 200 mas, about 300 systems are found with spectral types covering the majority of the HR diagram. A program aimed at systematically observing such a list of binaries with a complementary spectroscopic program to detect the secondaries could significantly increase the number of accurate stellar masses measured. The non-redundant array configuration shown below could be used to survey a large number of systems for multiplicity.

8. Stellar surfaces

The NPOI array was specifically designed to be operated in different configurations in which long baselines can be bootstrapped by tracking the fringes on shorter ones where the fringe contrast is high enough. This is because in the regime where the longest baselines begin to see surface structure on a stellar disk, the fringe contrast has dropped to very low levels as the disk is completely resolved.

For the imaging simulation shown below, we added Gaussian noise of $\sigma = 0.05$ to the real and imaginary part of the simulated complex visibilities. All 32 channels of the NPOI were used. Two iterations of phase self-calibration starting with a spherical component were performed while deconvolving the image with a Maximum Entropy algorithm (AIPS task VTESS). Compared to the widely

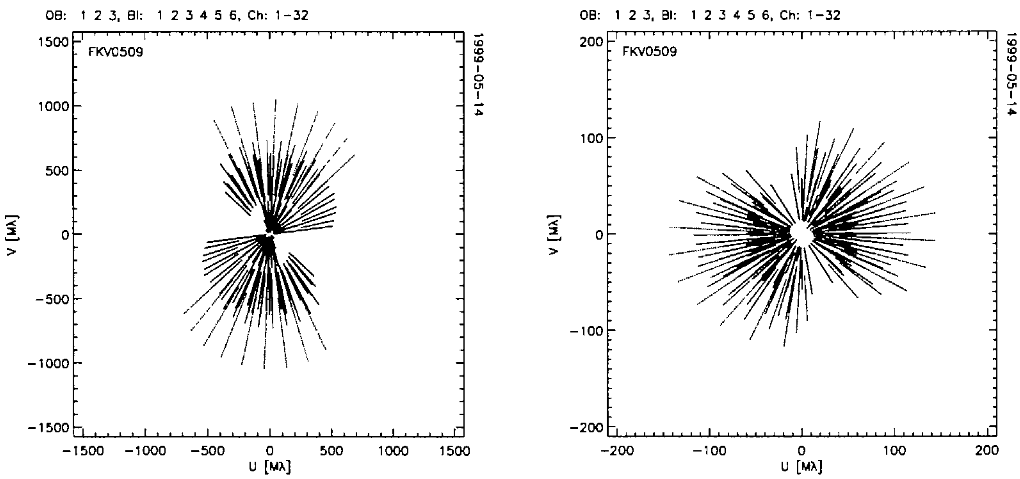

Figure 3. Earth-rotation aperture synthesis with a non-redundant survey configuration (left) and a redundant stellar disk imaging configuration (right).

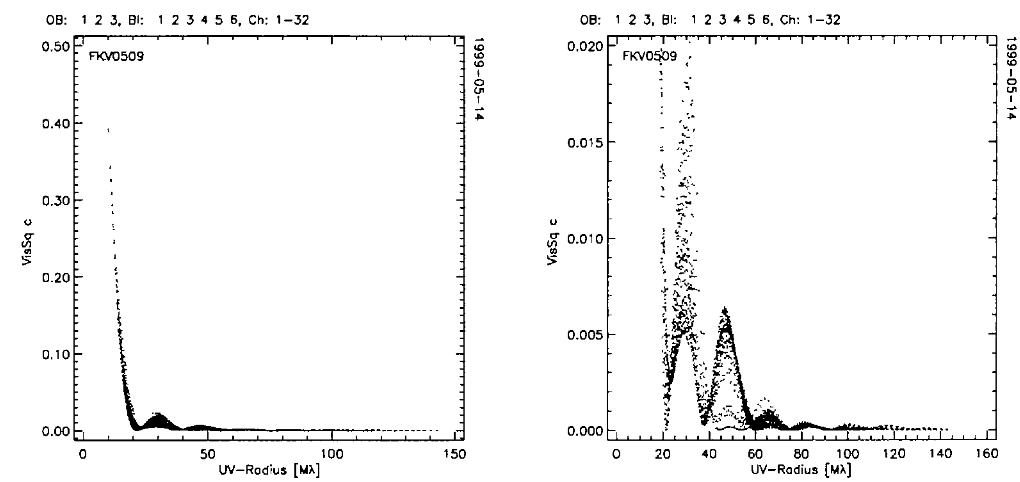

Figure 4. The squared visibility amplitude as a function of *uv*-radius for a 12 mas stellar disk observed with the redundant array configuration. Note the very low amplitudes at spacings with the most information of surface structures on the disk.

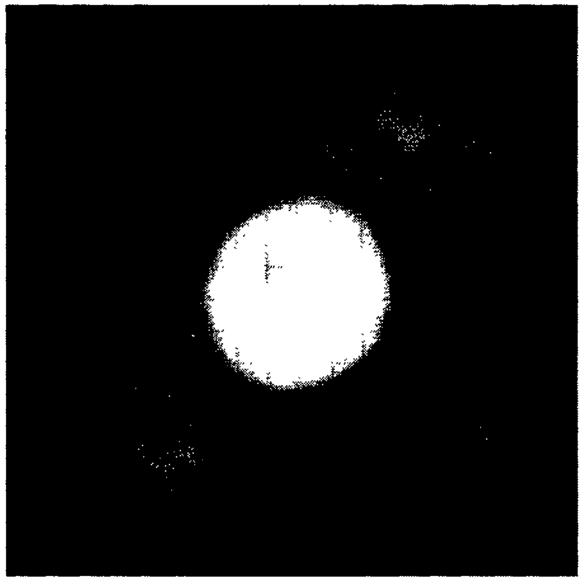

Figure 5. Image of a stellar spot using simulated data from NPOI in the redundant array configuration. The stellar disk is 12 mas in diameter, the spot diameter is 3 mas, the restoring beam is 2 mas. The spot has a temperature of 3500 K, whereas the star is a 5000 K limb darkened disk.

used CLEAN algorithm, the former is better suited for the large and low contrast area represented by the stellar disk.

Acknowledgments. This work has been done in collaboration with the NPOI team, and special thanks are due to the observers. Funding has been provided by the Office of Naval Research and the Oceanographer of the Navy.

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Discussion

Andrew Gould: How long until you measure those 164 stars with 1% mass precision?

Christian Hummel: Based on the Batten et al. Catalog of spectroscopic binary elements I selected all stars brighter than V=6, north of -10 degrees declination, and with estimated semimajor axes larger than 1 mas, and derived 164 for the number of components whose masses could be determined with better than 1% precision if the relative astrometry had a precision of 10 micro-as and the velocity amplitudes a precision of 50 m/s. These are difficult to achieve, but maybe not impossible. Such a project would take many years.

Vassilis Zarifis: What is the effect of the missing points in the (u,v) plane on the synthetic imaging?

Christian Hummel: Missing UV - points cause sidelobes around bright sources in the image. They can be effectively removed with the CLEAN algorithm. Large gaps in the UV plane, however, will degrade the image so much that only the simplest of source structure can be imaged.

Slava Turyshev, Stephen Unwin and Rudolf Danner