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Toward Complex Visibilities using Optical Interferometry: Multi-wavelength Phase Referencing

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ABSTRACT

We report on experiments in multi-wavelength phase referencing using the Navy Prototype Optical Interferometer (NPOI). In these experiments we use the unique capability of the NPOI to simultaneously observe 16 spectral channels covering 512-850 nm on multiple baselines simultaneously. We present observations of the well-known Be star ζ Tauri using custom filters which allow us to isolate the Hα line in a single spectral channel while the other channels observe the stellar continuum. Since the central star is unresolved, we can use the data in the continuum channels to calibrate the spectral line data. Using the phase information recovered in this way, it is possible for the first time to use standard techniques to construct simple images of the line-emitting region around the star.

Keywords: optical interferometry, imaging, Be stars, Hα emission lines

1. INTRODUCTION

1.1. The Quest for Complex Visibilities in Optical Interferometry

Imaging with a stellar interferometer is based on the van Citter-Zernike theorem[1]. This theorem states that the complex fringe visibility, ($Ve^{i\theta}$), measured by an interferometer is the Fourier transform of the source brightness distribution. Thus, in order to perform the Fourier transform we need to measure both the amplitude and phase of the visibility. In optical interferometry measuring the real and imaginary part of the visibility is, in general, not possible because the phase is corrupted by atmospheric turbulence, and, due to the nature of photon counting statistics, the unbiased estimator of the amplitude is V^2 rather that V. The challenge for optical interferometry, therefore, is to try to develop strategies to recover as much of the phase information as possible. An important group of strategies are those that use *phase referencing*.

1.2. Multi-wavelength Phase Referencing

One technique that can be used to recover phase information is multi-wavelength phase referencing[2]. The technique requires some *a priori* knowledge of the source spectrum and an interferometer equipped to observe a number of wavelengths simultaneously. The NPOI is such an instrument; in the observations reported here, visibility measurements were made on multiple baselines at 16 wavelengths simultaneously covering a band from 512 nm to 850 nm. As a result, the NPOI is uniquely suited for this type of phase referencing. The basic assumption is to use

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14. ABSTRACT
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knowledge about data in one part of the source spectrum to calibrate another part of the spectrum. There is a class of stars, called Be stars, which are ideally suited to this experiment.

1.3. Observing Be Stars with NPOI

Be stars are young hot stars in which the Balmer lines, especially Hα, are seen in emission. The emission lines are believed to arise in a thin disk of gas located in the equatorial plane of the star. The central star is small (< 0.5 mas) and can be considered unresolved, whereas the line-emitting disk can be several milliarcseconds in extent. Thus, the intrinsic phase in the spectral channels that do not include the line emission will be zero and can be used to calibrate the phase of the line channel. For this experiment, special interference filters were installed in front of the spectrometers to isolate the narrowband Hα emission in one channel, while the other channels observed the continuum emission from the stellar photosphere. This backend setup is describe in detail in Tycner *et al.*[3]

2. DATA ANALYSIS

In this section we discuss the steps used to construct complex visibilities from the raw observations of a Be star. The NPOI raw data consists of samples of the fringe visibility on each baseline at each wavelength every 2 ms, and these samples, along with ancillary data, are stored for subsequent off-line processing. A typical measurement (scan) lasts 30 seconds.

2.1. Coherent Averaging

The raw complex visibilities are coherently averaged for 200 ms using an algorithm developed by Hummel and described in Peterson *et al.*[4] (Sec. 3.2). This increases the signal-to-noise ratio, particularly in the bluest spectral channels. These coherent averages are called sub-scans. The algorithm attempts to track the phase change between successive 2 ms samples for 100 samples and then rotate the phases back to the first sample in the sequence.

2.2. Instrumental Phase Determination

We use the data from *all* calibrator stars to obtain values of the real part, the imaginary part, and the phase of the raw visibility averaged over the entire night. This grand average assumes that the air path and vacuum delay differences average to zero over the course of the night. The result is the instrumental phase as a function of wavenumber. Figure1 shows the data for a single baseline. The left-hand panel shows the variation of the individual coherently average sub-scans the make up a single 30-second measurement. The overall shape of the individual curves is due to uncompensated glass in the beam combiner, while the variations come from differential air path delay between the two siderostats. The effect of the uncompensated glass should remain constant, while the air path effects should average out over the night. That this is indeed the case can be seen in the right-hand panel where all the calibrator data was combined and fitted with a single curve.

2.3. Program Star Complex Visibilities

For the program stars, the coherently averaged sub-scans were further averaged incoherently for 30 seconds to produce an average real and imaginary part of the complex visibility. We then can calculate the amplitude and phase on each baseline.

2.4. Correcting for Instrumental Effects.

From the calculated phases for the program stars we can construct plots like those shown in Figure 2. We then subtract the instrumental contribution. The result, in Figure 3, is the intrinsic phase of the source plus a quadratic variation due to differential air path delays between the stations.

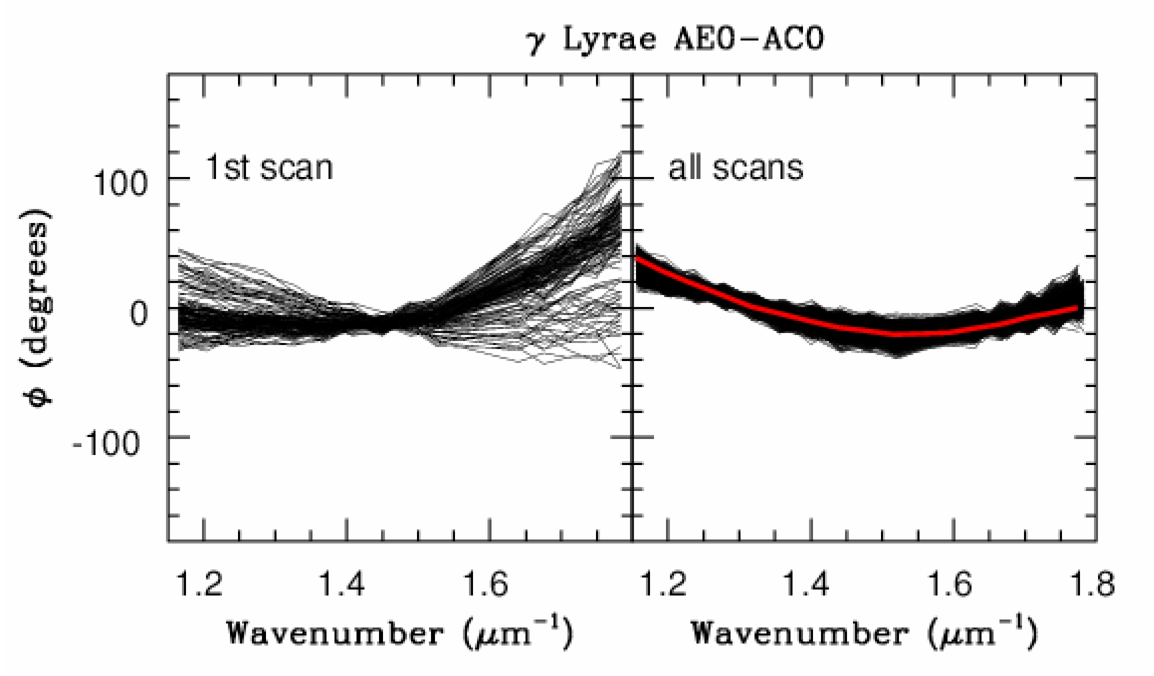

Fig. 1. Determining the instrumental phase variation with wavenumber for the calibrator γ Lyr. The left panel shows the 144 coherent sub-scans for one measurement, while the right panel shows the average of all the calibrator data for the entire night.

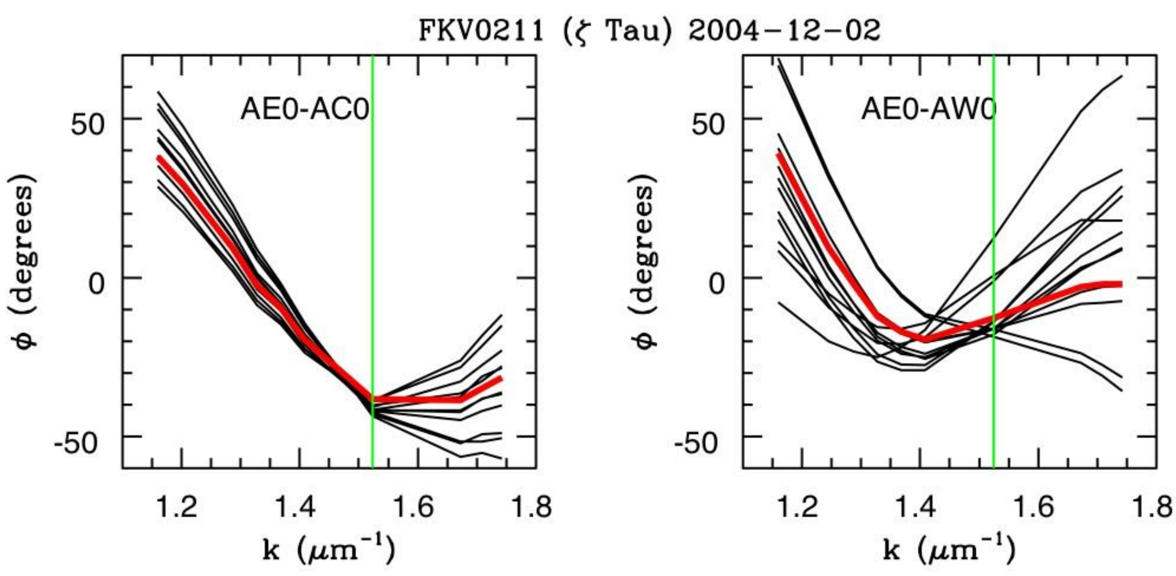

Fig. 2. Observed baseline phases for 2 baselines for the star ζ Tau before subtracting the instrumental phase variation. Each curve represents a 30-second measurement.

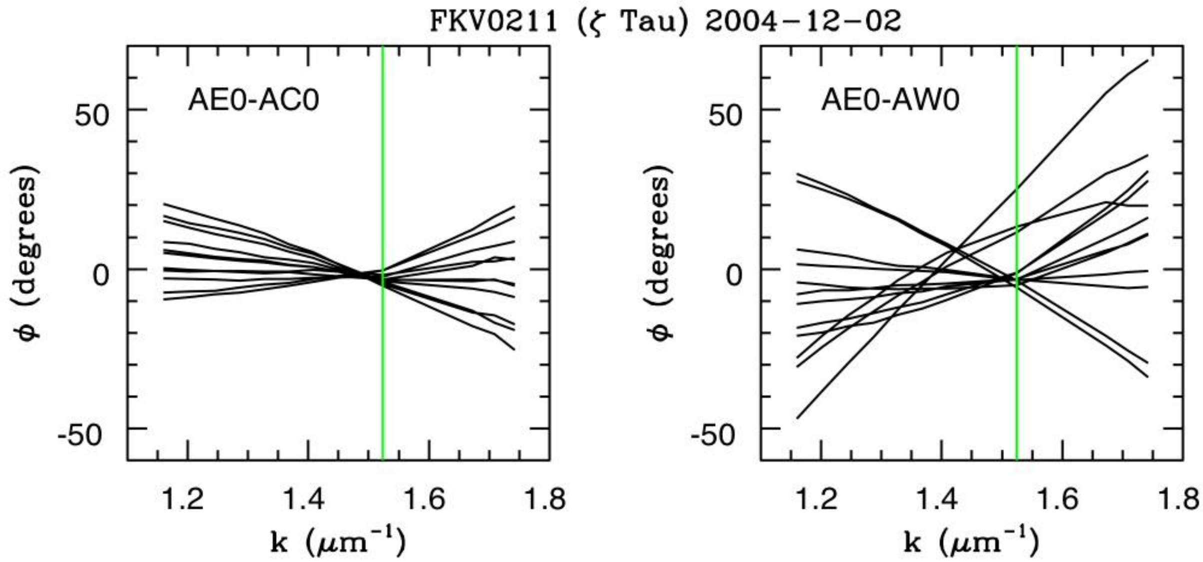

Fig.3. The baseline phases after subtracting the instrumental phase, but before fitting a quadratic function to the data outside the line.

2.5. Calculating the Phase at Hα

The central star is unresolved (< 0.5 mas), which means that the phase in the continuum channels can be taken to be zero. We fit a quadratic curve through all the channels outside the line channel and subtract this curve from all the channels including the line, yielding continuum phases that cluster around zero and an Hα phase that is typically a few degrees, as shown in Figure 4.

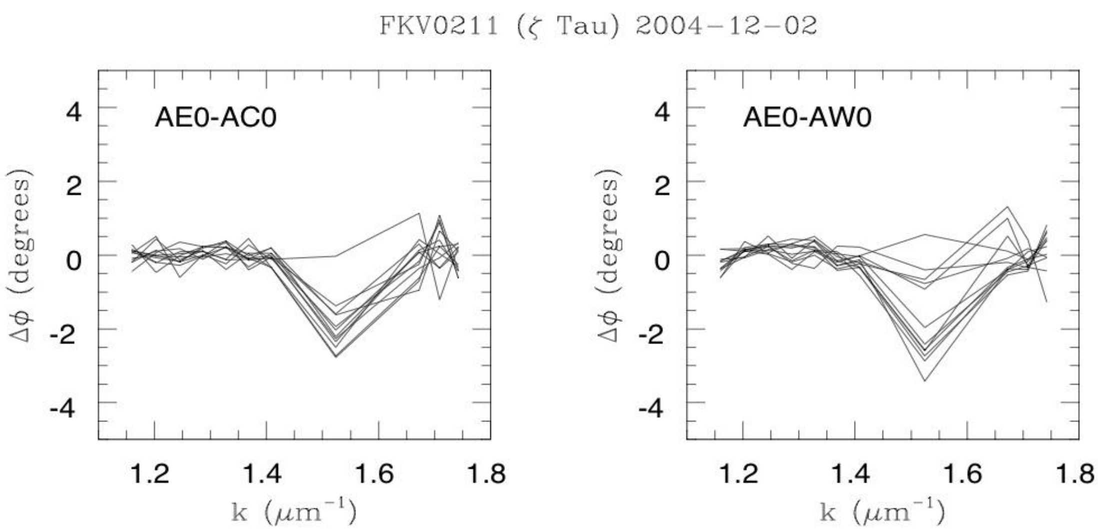

Fig. 4. The final baseline phases for 2 baselines after subtracting a quadratic curve fitted to the continuum data.

Additional details on the foregoing steps can be found in the paper by Schmitt *et al.*, published in these Proceedings.

2.6. Forming the Complex Visibilities

We calculate the complex visibilities for the line and continuum channels. Now the flux in the line channel suffers contamination from the stellar photosphere and must be removed. The correction is done in the Fourier plane by subtracting a scaled continuum vector calculated from the adjacent continuum channel on either side of the line channel.

2.7. Storing the results

The resultant complex visibilities are written to an OIFITS or UVFITS file with standard NPOI software.

2.8. Imaging

We make an image with standard radio synthesis imaging software such as AIPS or AIPS++. The phases are already calibrated, we simply Fourier transform the data and apply the CLEAN algorithm to the resultant image.

3. EXAMPLE - ζ TAURI

The well-known Be star, ζ Tauri, has been reported to have an asymmetric Hα envelope by Vakili *et al.*[5], based on spectrally resolved interferometry with the GI2T. NPOI observations of ζ Tauri were made on 7 March 2004 with narrowband Hα filters in place. Closure phase plots made from these observations suggest that the line emission region is asymmetric, so this data set appeared to be a good candidate for multi-wavelength phase referencing. Following the procedure outlined above, an image was made using all the continuum channels and another image was made using just the data in the Hα channel. These images are shown in Figure 5.

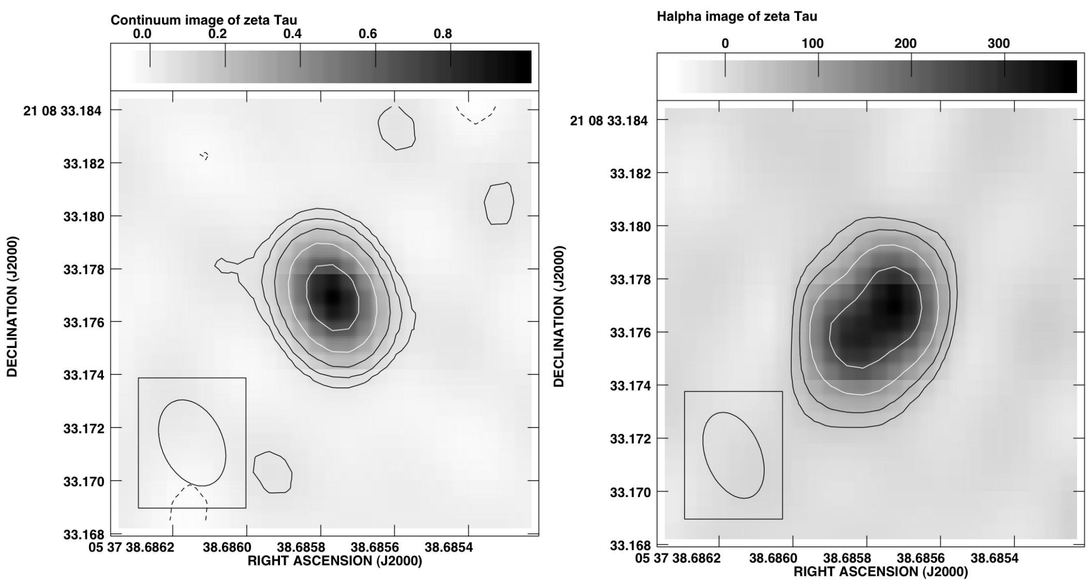

Fig. 5. Images of ζ Tauri in the stellar continuum (left) and the Hα line (right). The Hα emission is extended along a NW-SE direction, which is perpendicular to the major axis of the synthesized beam, and the intensity of the NW lobe is greater than the SE lobe. The continuum image mimics the synthesized beam and its peak intensity is centered between the two lobes of the Hα emission.

The image on the left in Figure 5 is constructed from the complex visibilities measured in the spectral channels that observe the continuum emission from the photosphere of the central star. Since the central star is unresolved, the image of the continuum emission simply mimics the synthesized beam, which is shown in the box in the lower left corner of the figure. The image on the right in Figure 5 shows the line-emitting region derived from the complex visibilities measured in the Hα channel alone. We see that the source in this image is extended roughly along a NW-SE axis; this axis is nearly perpendicular to the major axis of the synthesized beam, and it has two maxima separated by about 2.4 milliarcseconds. The intensity of the NW peak is about 1.16 times greater than the SE peak. The peak of the continuum image lies between the peaks in the Hα image, supporting the idea that the emitting gas is located in a disk around the star. In addition, the position angle of the major axis of the Hα emission agrees with the results of Quirrenbach *et al.*[6] and Tycner *et al.*[7] These results represent the first image made with complex visibilities of an asymmetric disk around a Be star using long-baseline optical interferometry.

4. CONCLUSION

This paper demonstrates that multi-wavelength phase referencing can be use to construct complex visibilities in optical interferometry. This has been done for the special case of Be stars, where the phases at wavelengths outside the emission line region can be used to calibrate the emission line phase. The derived complex visibilities have been processed with standard aperture synthesis imaging software packages (AIPS and AIPS++) to produce images of the continuum and line emission. The techniques described here were used to make an image of the Hα disk around the star ζ Tauri. This is the first time an image has been constructed from complex visibilities using optical long-baseline interferometry.

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