

Solving the Imaging Problem with Coherently Integrated Multiwavelength Data

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ABSTRACT

Recovering images from optical interferometric observations is one of the major challenges in the field. Unlike the case of observations at radio wavelengths, in the optical the atmospheric turbulence changes the phases on a very short time scale, which results in corrupted phase measurements. In order to overcome these limitations, several groups developed image reconstruction techniques based only on squared visibility and closure phase information, which are unaffected by atmospheric turbulence. We present the results of two techniques used by our group, which employed coherently integrated data from the Navy Prototype Optical Interferometer. Based on these techniques we were able to recover complex visibilities for several sources and image them using standard radio imaging software. We describe these techniques, the corrections applied to the data, present the images of a few sources, and discuss the implications of these results.

Keywords: optical interferometry, imaging, differential phases, self calibration, Be stars, binary stars

1. INTRODUCTION

Image reconstruction is one of the major challenges for optical interferometry. Unlike radio interferometry, where the atmosphere usually changes on long time scales, in optical interferometry the atmosphere fluctuates on times scales of a few ms, resulting in the corruption of the fringe visibility phases. Recently a lot of effort has been devoted by several groups in the development of imaging algorithms that use only squared visibilities (V^2) and closure phases, which are uncorrupted quantities (see Ref. 3,9,11 for a few examples). However, these techniques have to combine multiple measurements, like in the case of closure phases, so they contain less information, resulting in higher noise.

Therefore, one of the challenges to optical interferometric imaging is to recover as much of the phase information as possible. Here we describe two techniques developed by our group using coherently integrated data from the Navy Prototype Optical Interferometer (NPOI). The first technique uses differential phases to recover the phase information in the H α channel of Be stars, while the second one applies the phase self calibration method. These techniques allowed us to recover complex visibilities and image sources using radio interferometric reconstruction techniques.

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2. OBSERVATIONS

Our observations were taken with the NPOI,¹ on several nights between January 2004 and May 2005. All the observations were made with two spectrographs, simultaneously recording fringes in 16 spectral channels in the wavelength range 560–860 nm. We observed between one and three baselines in each spectrograph, with maximum baseline lengths ranging from 19 to 64 m. Each star was observed several times during the night (at least 3 scans), and their observations were interleaved with observations of suitable calibrator stars. The NPOI records fringe frames at a rate of 2 ms, and a typical scan lasts 30 s.

The data reductions followed 2 separate steps. First we used the standard incoherent integration method, where the data is processed to produce V^2 's averaged into 1 s points. These data are flagged to delete points with bad pointing and fringe delay tracking,⁸ and averaged to one spectrum per scan, which is bias corrected and calibrated. These V^2 's are used to estimate the amplitudes of the complex visibilities.

The second step of the data reductions is the coherent integration of the observations. We used the technique presented by Ref. 7 (see Ref. 10 and Jorgensen's contribution to this conference for more details on improvements and other applications of this technique). We align the 2 ms phasors and average the complex visibilities in 200 ms subscans, to increase the S/N. These subscans are flagged and the visibility phases are calculated.

3. DIFFERENTIAL PHASES

The differential phases are used in one of the techniques developed by our group to correct for the effects of the instrument and the atmosphere on complex visibilities (see Ref.14,16 for a detailed description of the technique, and Ref. 13,15 for a discussion on the differential phases method). This technique uses a priori information about the structure of the source at one wavelength to correct the observed phases and extrapolate this correction to the wavelength of interest. We apply this technique to the $H\alpha$ channel of Be stars. The photosphere of these stars is usually unresolved by our continuum observations (diameter <1 mas), while the $H\alpha$ emission comes from a disk with a size of a few mas. Since the photosphere of the star is expected to be circularly symmetric, the intrinsic phase of the continuum channels should be zero, making them ideal reference points for the application of this technique. Differential $H\alpha$ phases was used by Ref. 18,19 to study P Cygni and ζ Tauri and infer asymmetric structures in the emission line regions of these sources.

Of key importance to this technique is the availability of simultaneous multiwavelength observations, making the NPOI a well suited instrument for this application. We have that the observed phase consists of three terms, the intrinsic phase of the source (ϕ_0), an atmospheric (ϕ_{atm}) and an instrumental (ϕ_{inst}) components:

$$\phi_{obs} = \phi_0 + \phi_{atm} + \phi_{inst} . \quad (1)$$

All terms have implicit wavelength dependencies. The idea behind this technique is to find ways to correct the ϕ_{atm} and ϕ_{inst} contributions to ϕ_{obs} , which will leave us only with the phase due to the source (ϕ_0). In the case of the NPOI, ϕ_{inst} is stable, and can be determined using calibration stars, which are circularly symmetric and should have $\phi_0 = 0$. Since the effect of the atmosphere is random and additive, one can average all the scans of calibrators observed throughout the night, and the atmospheric term (ϕ_{atm}) should vanish, leaving us only with the instrumental term.

In the case of the Be stars we subtract the instrumental phase from the observed ones and are left with $\phi_0 + \phi_{atm}$. Since the phase in the continuum channels of these stars is expected to be zero, or at least very close to zero, we can determine ϕ_{atm} by fitting a second order polynomial to the continuum channel phases, and interpolate over the $H\alpha$ channel. A final correction that has to be applied to the data is the subtraction of the amount of continuum emission contribution to the $H\alpha$ channel. Once these corrections are done, one can calculate the complex visibilities using these phases and the V^2 's from the incoherent integration, and create a FITS file that can be used with standard radio interferometry software (e.g. AIPS²⁰).

In Figure 1 we show the differential phase results of β Lyrae.¹⁶ This star is an eclipsing binary with a separation of ~ 1 mas, where one of the components filled its Roche lobe and is transferring material to the other component. The gainer is surrounded by a disk of gas, which shows strong $H\alpha$ emission.⁵ Our observations did not fully resolve the binary system in the continuum, however, we can see in Figure 1 that we detect the

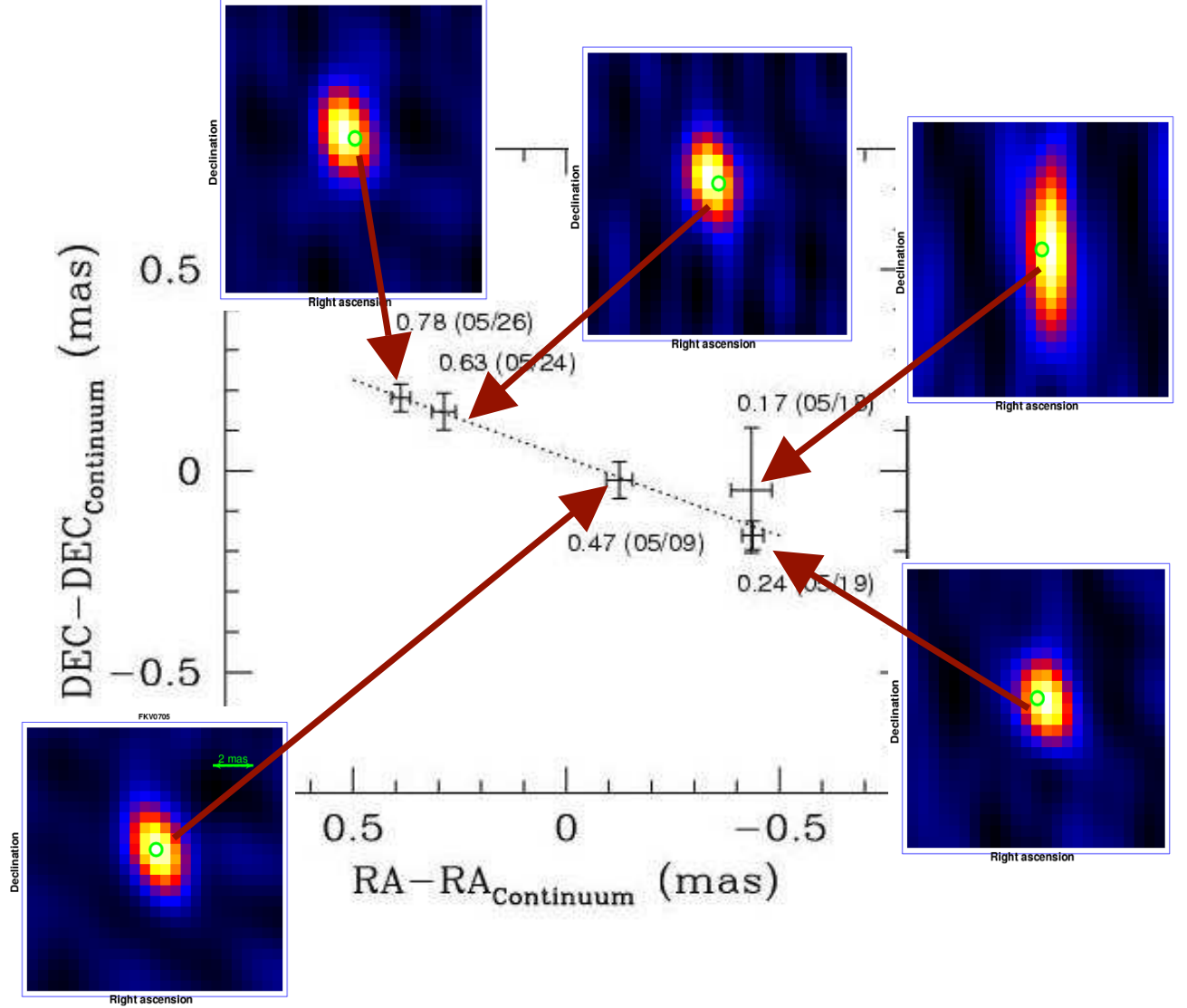


Figure 1. Mosaic of the measured orbit of β Lyrae, calculated by measuring the displacement of the $H\alpha$ photocenter relative to the continuum photocenter, and the corresponding $H\alpha$ image for each epoch. We indicate besides each point the orbital phase and date of the observations in 2005. The white star in the $H\alpha$ images shows the position of the continuum photocenter. Throughout this paper we show the deconvolving beam in the bottom left corner of each image panel. The lowest contour level corresponds to 3σ above the background level, with the levels increasing by $3\sigma \times 2^n$ steps.

displacement of the $H\alpha$ emission relative to the continuum photocenter. Based on these images we can determine that the position angle of the orbit is $\sim 67.7^\circ$, in agreement with the position angle of the radio emission¹⁷ and spectropolarimetry results.⁶

4. SELF CALIBRATION

The second technique used by our group to recover complex visibility information from NPOI observations combines most of the processing done for the differential phases, and self calibration.⁴ The data reductions follow the steps described above. We use the observed phases obtained from the coherent integration and correct them for the instrumental effects. This leaves us with baseline phases, which are composed of a component intrinsic to the source (ϕ_0) and a component due to the atmosphere (ϕ_{atm}). These phases are combined with

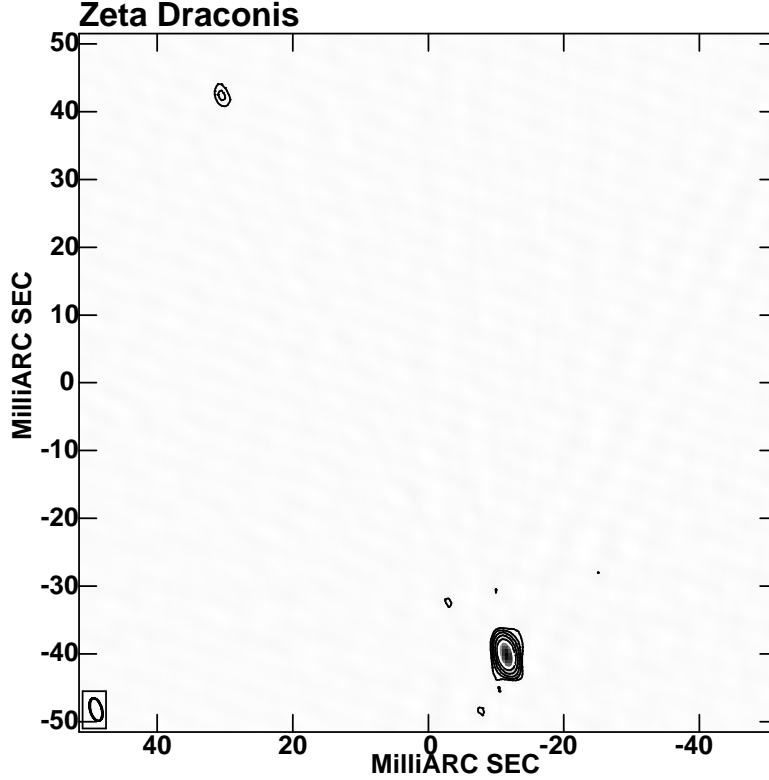


Figure 2. First phase self-calibrated image of the binary star ζ Draconis. Based on this image we measure $\rho = 92.62\text{mas}$ and $\theta = 26.9^\circ$, which are confirmed with a traditional fit to the V^2 and triple phases of this source.

the V^2 's, obtained from the incoherently averaged data, to calculate the complex visibilities of the source. These visibilities are converted to a FITS file and imported into AIPS, where we correct the atmospheric effect on the phases using the phase self calibration technique, widely used in radio interferometry. A requirement for this technique to work is the simultaneous observation of three or more baselines from which closure phases can be obtained. This information is needed in order to remove the atmospheric effects and recover the intrinsic source phases.

We show in Figure 2 the results of this technique applied to the observations of the binary system ζ Draconis. The Figure shows the image obtained after one iteration cycle of phase self calibration, created using all the channels. The measured separation and position angle between the 2 sources agree with the values obtained from the V^2 fits. Given the width of our channels and the separation between the 2 stars, bandwidth smearing causes a noticeable reduction in the flux of the fainter source, which should be taken into account in the measurements. The dynamic range of this image is ~ 100 . Although we could do additional phase self calibration iterations, we find that in this case the improvement to the image quality is not significant.

In Figure 3 we show the image of the binary system κ Ursa Majoris, obtained after two phase self calibration iteration cycles. We measure the separation and position angle between the two sources, which agree very well with the published ephemerides of this source. As an alternative confirmation of these results we use the parameters measured from this image to create a model and calculate the expected V^2 's and triple phases of this system. The results from this model are compared to the observed V^2 's and triple phases in Figure 4, where we can see that there is a good agreement between the model and the measurements.

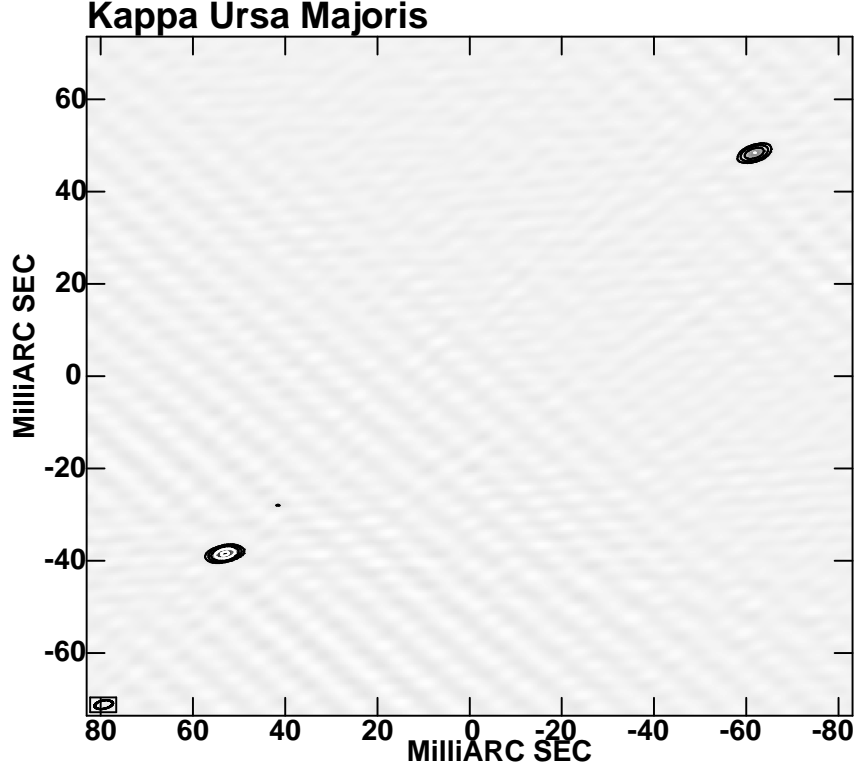


Figure 3. Image of κ Ursa Majoris obtained after the second phase self calibration iteration. We measure $\rho = 143.89$ mas and $\theta = 306.9^\circ$, in good agreement with the ephemerides of this source.¹²

In Figure 5 we show the application of this technique to a more complicated source, the triple system η Virginis. The image shows the inner binary, separated by 5.53 mas along p.a.= 306.1° , while the outer component is separated by 109.03 mas along p.a.= 199.0° , relative to the photocenter of the inner pair. These measurements agree with the ephemerides published by Ref. 7.

Finally, in Figure 6 we show another 2 binary systems, θ^2 Tauri and ϕ Herculis. Again, the separations and position angles of the components agree with their published ephemerides.^{2, 21}

5. SUMMARY

In this paper we discussed the development of two techniques that used coherently averaged NPOI data to recover complex visibilities. This allowed us to image the sources using standard radio interferometry imaging methods. Using the first technique, differential phases, we were able to correct the instrumental and atmospheric contribution to the intrinsic $H\alpha$ phases of β Lyrae, being able to image the line emission in this source and detect its movement relative to the continuum photocenter. Although this is a powerful technique, it requires a priori knowledge about the structure of the source at some wavelength, and has a limited number of applications. The second technique, self calibration, was used to correct the atmospheric effects to the observed phases, allowing us to image binary and triple systems. This technique is extensively used in radio interferometry, requires closure phases, but is applicable to a wider range of sources. Future plans include the application of this technique to other sources, like rapidly rotating stars, stars with spots and disks, among other sources.

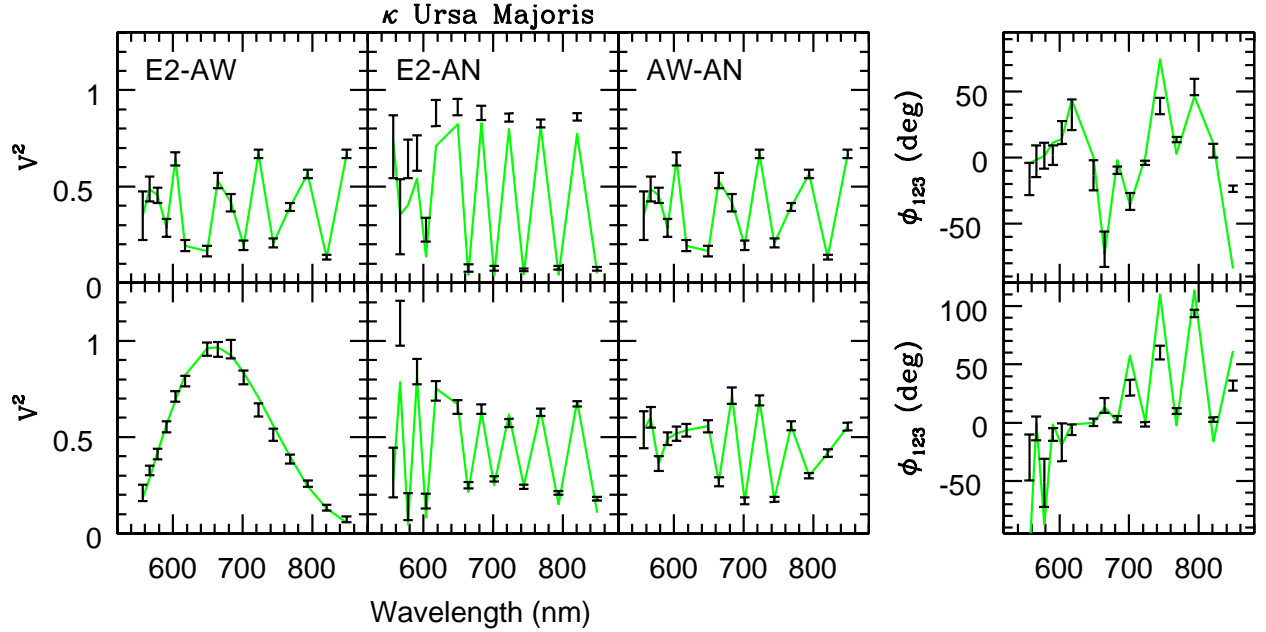


Figure 4. Measured V^2 's and triple phases of two scans of κ Ursa Majoris are shown as error bars. The solid line shows the model calculated using the parameters measured in the image presented in Figure 3.

We would like to point out that the techniques presented here make use of all the information collected by the interferometer and do not combine multiple measurements (e.g. closure phases), like in the case of imaging methods that use only V^2 's and closure phases. Consequently we should be able to obtain higher precision measurements and/or higher dynamic range images of astrophysical sources.

ACKNOWLEDGMENTS

The work done with the NPOI was performed through a collaboration between the Naval Research Laboratory and the US Naval Observatory, in association with Lowell Observatory, and was funded by the Office of Naval Research and the Oceanographer of the Navy. Basic research in optical interferometry at the NRL is supported by 6.1 Base funding. We thank the NPOI staff for the careful observations that contributed to this work. This research has made use of the SIMBAD literature database, operated at CDS, Strasbourg, France. We would like to thank Christian Hummel for the availability of the data reduction package OYSTER.

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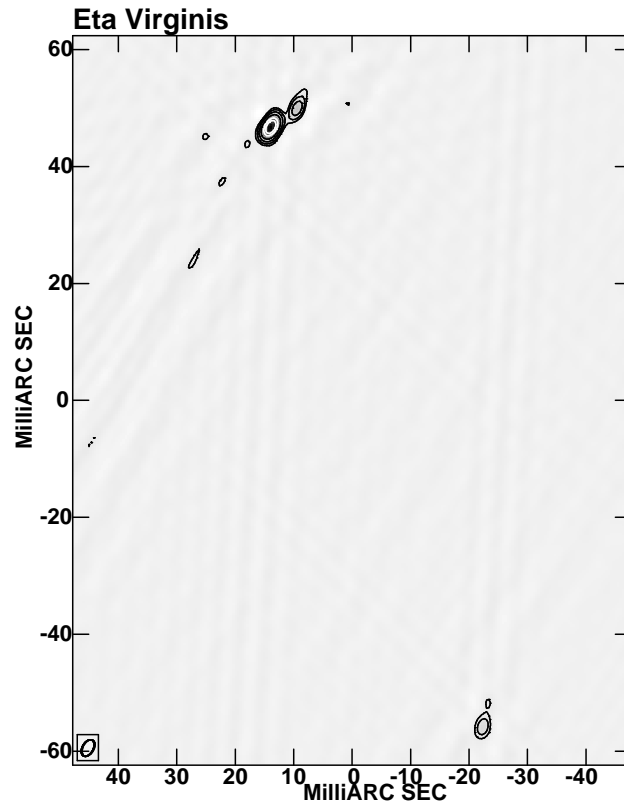


Figure 5. Image of η Virginis obtained after the second phase self calibration iteration.

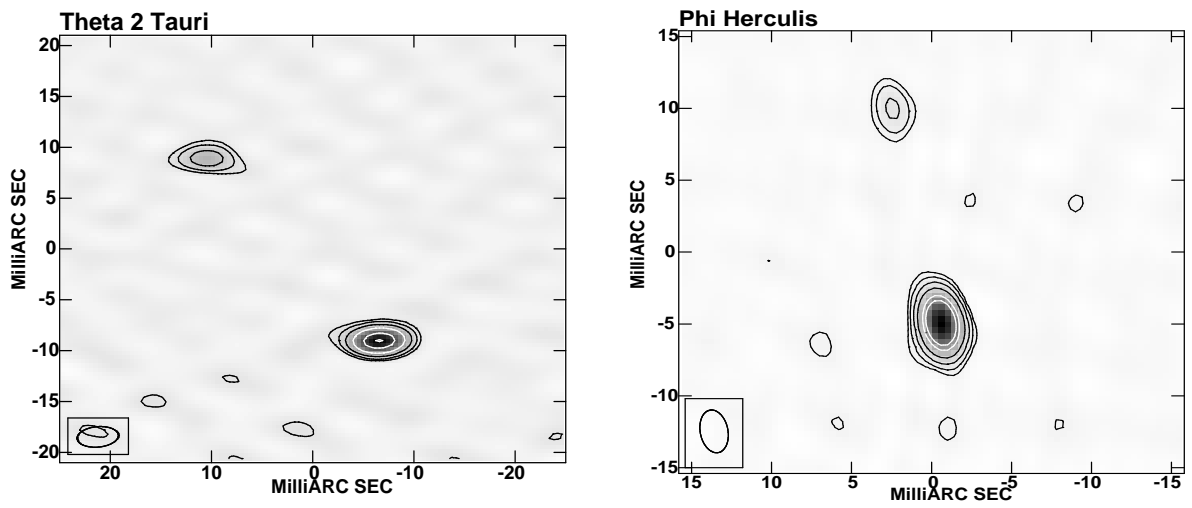


Figure 6. Images of θ^2 Tauri (left) and ϕ Herculis (right), obtained after one phase self-calibration iteration.

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