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Stars, Companions, and their Interacions: A Memorial to Robert H. Koch

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Optical Observations with Milliarcsecond Resolution of Stars, Their Environments and Companions

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Observations with milliarcsecond resolution using the Navy Optical Interferometer have been obtained for a number of stellar systems which include high-mass binaries, eclipsing binaries, and radio stars. These observations also reveal the previously unseen companions in single-lined spectroscopic binaries via directly measured flux ratios. We will present examples of published and ongoing research efforts of these systems to illustrate how an optical interferometer contributes to our knowledge of stars, their environment, and companions. These studies include a conclusive revealing of the previously unseen companion in the single-lined binary Φ Herculis, the direct determination of orbital parameters in the wide and close orbits of Algol, and revealing the orbit of β Lyrae with spatially resolved images of the Hα emission.

Keywords: optical interferometry, binaries, astrometry, Navy Optical Interferometer

1. INTRODUCTION

The Navy Optical Interferometer (NOI), formerly the Navy Prototype Optical Interferometer (NPOI), is a joint project of the Naval Research Laboratory (NRL), and the United States Naval Observatory (USNO) in cooperation with Lowell Observatory, located at Anderson Mesa near Flagstaff, Arizona. For further instrument details see Armstrong et al. (1998) and for details regarding NOI's observations and data reductions see Hummel et al. (2003), and the references therein.

Optical interferometry offers a method of directly determining stellar diameters, the morphology of Hα emission regions, and astrometric orbital parameters that govern the interactions of binary systems. The fundamental observed quantity for the NOI is the squared visibility (V^2, Armstrong et al. 1998), which is the Fourier transform of the source brightness distribution (see Thompson et al. 2001 for an introduction to interferometry). After detecting interference fringes from a binary star an orbit may be fit (Pan et al. 1993). With the orbit, the visibility data from all observations can be used to fit for the magnitude differences of the binary system in question (Hummel et al. 2003). Results of this technique as applied to the binary stars Phi Herculis, Beta Lyrae and Algol are reviewed in this work.

2. RESOLUTION OF SINGLE-LINED SPECTROSCOPIC BINARIES: Φ HERCULIS

Φ Herculis (HD 145389, HR 6023) is a mercury-manganese (HgMn) star, showing a wide variety of spectral abundance anomalies with both depletions and enhancements (Adelman et al. 2004). Aikman (1976) identified Φ Her as a single-lined spectroscopic binary. The secondary component avoided detection until NOI observations became available beginning in 1998. These interferometric observations lead to the identification of the spectral type of the secondary. Identification of the secondary's spec-

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tral type enables a better understanding of the chemical abundances of the primary.

In Fig. 1 the calibrated V^2 data shows the cosine wave signature of a binary source (Michelson 1920) as seen with an interferometer. As described in Pan et al. (1993) and Hummel et al. (2003), a fit for the binary parameters was applied and a measure of the magnitude difference of the secondary relative to the primary was found. With the assumption that both stars are on the main sequence and with the determination of the magnitude differences, 2.57 in the V band and 2.39 in the R band, a prediction of the secondary's spectral type as A8 V was found. This spectral type was verified spectroscopically with follow up observations utilizing Dominion Astrophysical Observatory (DAO) spectra (Zavala et al. 2007). An independent confirmation of the secondary spectral type was also made by Dworetsky & Willatt (2006).

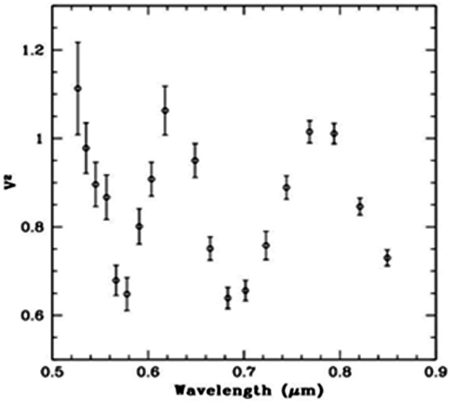

Fig. 1. The calibrated squared visibilities of Φ Her for Navy Optical Interferometer observations made on 1998 May 16. This data shows the characteristic cosine wave signature of a binary.

Fig. 2 illustrates how the synthetic spectra of the components, constrained by the brightness ratio from the NOI, accurately represent the observed spectra. In the right panel of Fig. 2 the DAO spectra are shown with an overlay of the summed synthetic spectra for both Φ Her A and B. In the left panel of Fig. 2 the DAO observed spectra is overlaid on individual normalized synthetic spectra for Φ Her A and B.

3. HA EMISSION IMAGING AND ORBIT DETERMINATION: B LYRAE

β Lyrae is an interacting eclipsing binary system consisting of a ~3 solar mass B6-8II star which has filled its Roche lobe and a ~13 solar mass early B star, which is completely obscured and hidden within a thick accretion disk (Harmanec 2002). In 2002 the NOI observed β Lyrae as part of an experiment to detect the binarity of this system and the Hα emission associated with the accretion stream. NOI data from this experiment is presented along with images indicating the position of the Hα emitting regions relative to the continuum photo-center as a function of orbital phase, providing a means for analyzing the Hα morphology (Schmitt et al. 2009).

In Fig. 3 (left panel) the position of the Hα emission is plotted relative to the continuum photo-center for the five nights of data. The orbit of the Hα emission is also plotted by fitting a line to the data points with an orbital solution found to be oriented along a position angle of 248.8 ± 1.7°. Using parameters derived by Harmanec et al. (1996), Linnell (2000), and Harmanec (2002), the orbits of the Hα and continuum photo-centers were fit and converted to positions in the sky using the inclination de-

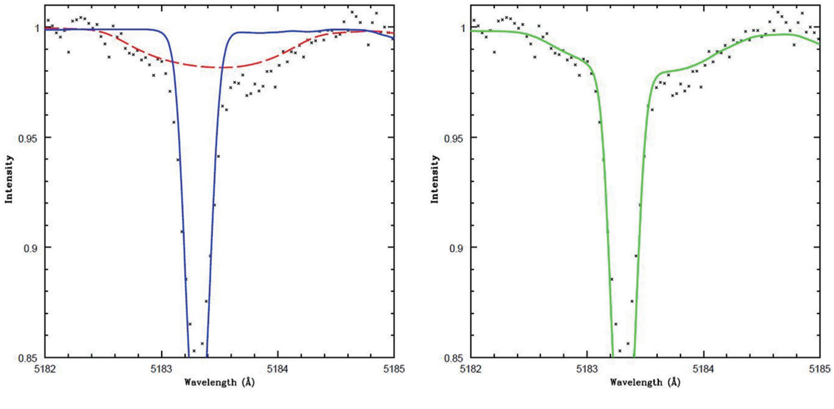

Fig. 2. The left panel shows the observed spectra overlaid on normalized synthetic spectra for Φ Her A (solid blue line) and Φ Her B (red dashed line). In these images we can see the primary and secondary components of Mg I (2) 5183.6042. In the right panel is the same data but now is overlaid with a line representing the summed synthetic spectra for Φ Her A and B.

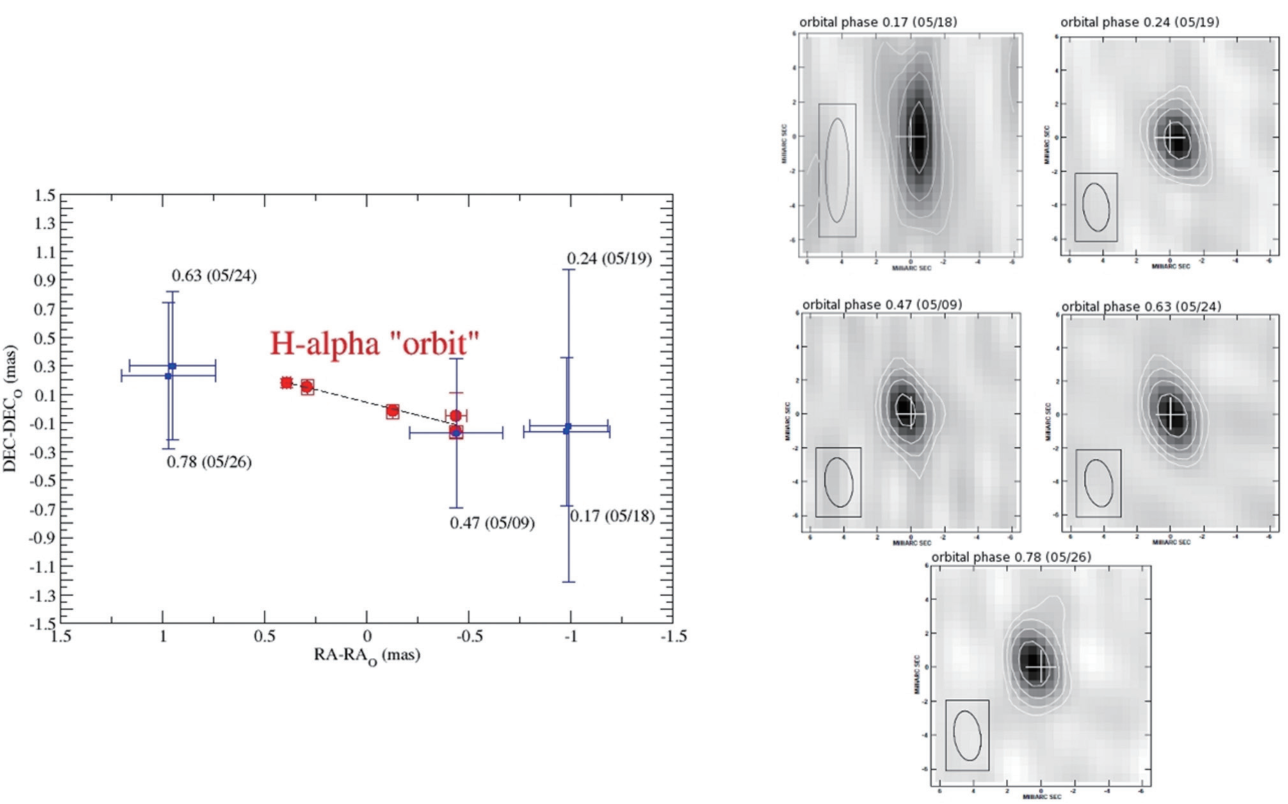

Fig. 3. Separation of the two binary components (left panel, blue data points with larger errors), with each point showing the uncertainty in the position of the separation of the two sources. Besides each point an indication of the orbital phase and the date is given along with a dotted line representing a least squares fit to the data. The dotted line gives the orbit in the plane of the sky. The position of the peak of Hα emission relative to the continuum photo-center is also displayed within the left panel (red square data points). The series of panels on the right show the Hα images of β Lyrae. Each panel corresponds to a different night and is organized, in a clockwise fashion, of increasing orbital phase. The white star points to the photo-center of the system. The lowest contour in each figure corresponds to the 3σ level. The reconstructing beam size and orientation is shown in the bottom left corner of each panel.

rived by Linnell et al. (1998). One important observational result is the Hα semi-major axis was observed to be less than the continuum semi-major axis, providing evidence that the NOI was effectively imaging the orbit of this system. This is due to the Hα emission originating within the disk of the more massive star, and the continuum photo-center being located nearer the less massive star (Schmitt et al. 2009). These Hα images each correspond to a different night and are organized in order of increasing orbital phase and are also shown with the correct orbital orientation.

4. DIRECT DETERMINATION OF ORBITAL PARAMETERS: ALGOL

Algol is the prototype for a well-known class of eclipsing binaries. The Algol system is a hierarchical triple system (close binary Algol A-B and triple Algol AB-C) and is well summarized by Söderhjelm (1980). Speckle (Labeyrie et al. 1974) and optical (Pan et al. 1993) interferometry resolved the orbit of the AB-C component, but the ascending node of these orbits differed by 180° from that used in the High Precision PARallaxCOllectingSatellite (HIPPARCOS) double star solution (Lindegren et al. 1997). As Algol is 1 of 12 radio stars used to link the HIPPARCOS optical reference frame to the International Celestial Reference System (ICRS, Kovalevsky et al. 1997), a resolution of this 180° ambiguity was needed to reconcile the time-variable systematic offset of the photo-center between the HIPPARCOS orbital orientation and the interferometric orientation.

Interferometric observations using the NOI have resulted in the first resolved images of the triple system, as seen in Figs. 4 and 5. These observations have led to an unambiguous determination that the close pair orbit (A-B) is retrograde and nearly orthogonal to the plane of the wide (AB-C) orbit (Zavala et al. 2010). The improvements made to the AB-C orbital plane orientation have removed the time-variable systematic offset expected

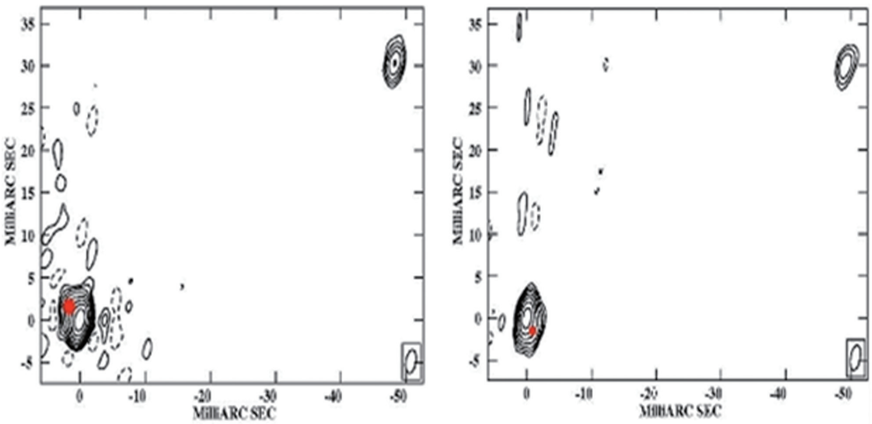

Fig. 4. Images of the Algol triple system made from Navy Optical Interferometer data on 2006 Oct 29 are seen in the left panel. In the right panel observations from 2006 Oct 30 are shown to emphasize the motion of Algol B between the two epochs. The Algol C component can be found in the upper right hand of each panel. To help guide the eye, the approximate positions of Algol B are indicated at each epoch by a filled in red circle.

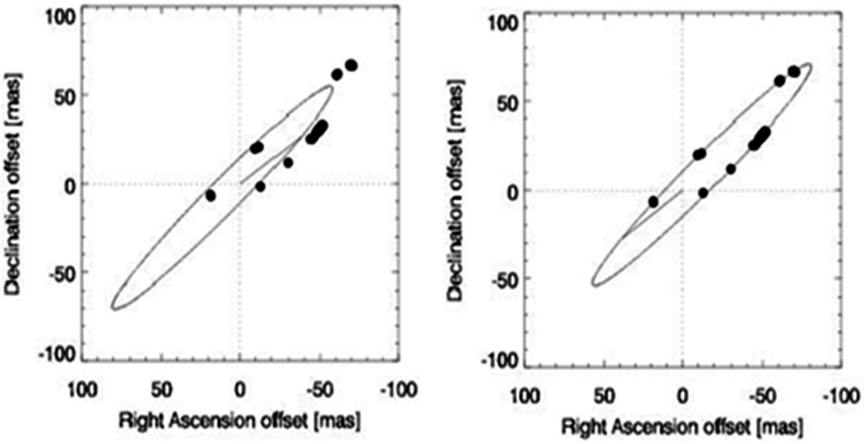

Fig. 5. The left panel is an illustration showing the Navy Optical Interferometer (NOI) astrometric results for the AB-C orbit superposed on top of previously determined orbits from Mark III and CHARA observations. In the right panel an illustration of NOI astrometric results are plotted with the astrometry of Pan et al. (1993) and rotated by 180°. A vector from the origin indicates the periastron point.

between the orbit used in the HIPPARCOS solution and the results of Pan et al. (1993) and Csizmadia et al. (2009). NOI observations have also led to the first directly measured magnitude differences for the three stars in Algol. Estimates made in previous studies were performed by modeling photometric light curve and spectroscopic data and spanned more than one magnitude, from 3.92 ± 0.88 (Richards et al. 1988) to 2.71 ± 0.15 (Kim 1989). The NOI directly measured V band magnitude difference favored a magnitude less than 3 (Zavala et al. 2010).

NOI magnitude differences help to constrain results obtained by modeling photometric light curves and spectroscopic data by adding directly measured Δ-magnitude results. Due to the NOIs capability of directly measuring position angles and magnitude differences in close binaries, further observations of double and triple star systems will also benefit from the directly measured fundamental parameters that govern these dynamic stellar systems.

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