Adventures in Interferometry

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Abstract -- While the Michelson Interferometer examined starlight atop the Mt. Wilson 100 inch telescope nearly 100 years ago, it's taken decades for interferometric instrumentation to begin to enter the mainstream of astrophysics. We report on one application of these methods: measuring the near infrared angular diameter of the eclipsing binary star, epsilon Aurigae, using the 100 meter Palomar Testbed Interferometer located adjacent to the more famous 200 inch telescope atop Mt. Palomar.

1. Introduction to Interferometry

Astronomical interferometry is a century old technique of combining light from two or more telescopes, which has matured greatly in the beginning of the 21st century. For example, the European Union has invested more than $500M in the Very Large Telescope (VLT) Interferometer at Paranal, Chile, a combination of four 8-meter plus auxiliary telescopes. When light from two different telescopes is combined, it will constructively interfere when the exact path difference between telescopes is zero. Small differences then will produce destructive or constructive combinations of the light depending on the ratio of wavelength to distance separating the telescopes. Given a known wavelength and separation of two telescopes, one obtains angular resolution equivalent to a telescope with an effective diameter equivalent to the separation. This is exactly the same as with a single telescope, but in combination, apertures of 100 meters and more are possible, yielding angular resolution of milli-arcseconds. The unit of arcseconds is 1/3600 of a degree in the degrees, minutes, seconds angular scheme. Radio telescopes have used this method much longer and have achieved micro-arcsecond resolution with very long baseline interferometry. However, this resolution is achieved only along one line across the star, set by the baseline orientation. As such, a single diameter along one azimuth can be obtained per observation. To construct an image requires continuing observation over many baselines and/or using earth's rotation to sample more azimuthal information on the star. This technique, called aperture synthesis, is highly evolved among radio astronomy practitioners, but is under development for optical interferometry.

2. Interferometric goals relative to epsilon Aurigae

The bright star, epsilon Aurigae has been known for over a century as an Algol-like eclipsing binary with a very long period. The oddity with the star is that the companion causing the eclipses cannot otherwise be easily detected – even during eclipse the primary star light dims but is largely unchanged, give or take a shell spectrum detected at high spectral resolution optically and in the near infrared during the 1983 eclipse (Lambert & Sawyer, 1986; Hinkle and Simon 1987). Current models for epsilon Aur suggest an opaque disk does the eclipsing (Carroll et al. 1991). The estimated distance of 625 parsec to epsilon Aur and the binary separation 27.6 AU, imply that the binary should exhibit an angular extent of 44 milli-arcseconds. The F superigant star has a radius of nominally 200 solar radii, or nearly 1AU across (Carroll et al. 1991), and should exhibit an angular size of nearly 3 milli-arcseconds. This value is greater than the reported value by Nordgren et al.

(2001) of a broadband optical NPOI diameter for epsilon Aur (HR 1605) as 2.18 milli-arcsec (uniform disk) and 2.28 milli-arcsec (limb-darkened) within 4 percent errors, and slightly smaller than the diameter and distance factors would imply (see below). The secondary – opaque disk – nominally spans about 10 times that dimension. Additionally, epsilon Aur shows an irregular out-of-eclipse light variation of 0.2 mag, which some authors have ascribed to pulsation of the F star. These facts motivated us to seek out interferometry observing opportunities to confirm the pre-eclipse F star diameter, hunt for possible pulsational evidence therein, and set the stage for the eclipse when the disk transit would change the interferometric appearance of the F star.

3. PTI Operational details, a visual tour

We were awarded observing time with the Palomar Testbed Interferometer [PTI] for the winter season 2007-08 in order to monitor epsilon Aurigae in the near infrared (K band, 2.2 microns). PTI is located about 100 meters north of the 200 inch Hale telescope. It consists of three separate 16 inch telescopes (the huts) where the light is collected. This establishes three different baselines that can be used either in pairs, or all three together, depending on the needs of the observer. Within the huts are optical benches which perform two key functions, adaptive optics setup to correct for atmospheric aberrations, and a system of mirrors that convert the light collected to a collimated 4 inch beam which then enters into the long light tubes to bring the beams into the central facility.

Figure 1. The Palomar Testbed Interferometer as seen from the catwalk of the famous 200 inch telescope. Details at: http://msc.caltech.edu/missions/Palomar/

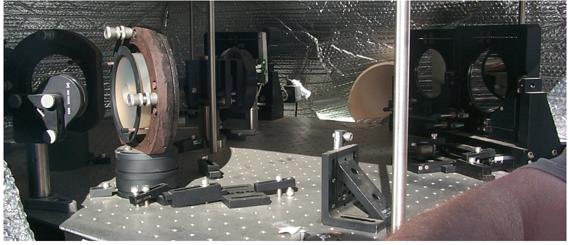


Figure 2. Optical bench within each of the huts.

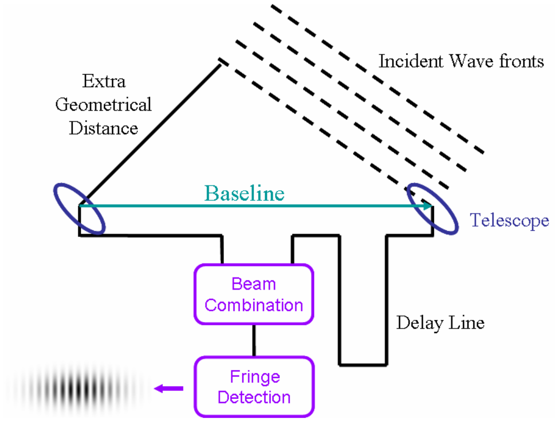


Figure 3. Diagram of basic function of the interferometer.

When light from different telescopes is combined, it will constructively interfere when a zero path difference is achieved. This is achieved through the use of delay lines within the central facility.

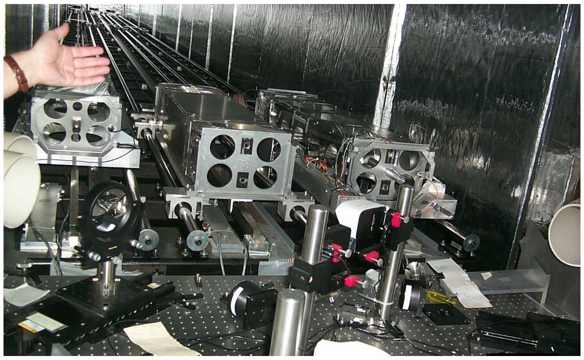


Figure 4. The delay lines consist of a series of carts which travel down their rails. The light paths from the telescopes enter the system in the tubes visible to the far right and left.

These can be seen in Figure 4. The optical bench shown here is a combination of where the beam combinations occur and the delay lines. What is not visible in Figure 4 is the beam of a helium-neon laser which travels from the optical bench down the rails to enter the holes seen on the carts and are reflected back to detectors which then count and keep track of the total number of wavelengths for each cart. In this way the precise positioning of the carts allows the delay lines to compensate for the varying baseline as the earth rotates such that the wave fronts can be recombined to allow for interference. This is known as metrology, and is the most difficult aspect of interferometry because it must be controlled at the level of the wavelength observed (microns) or better. This is achieved more easily with radio telescopes because the radio-waves are so much longer. Only within the past two decades has the technology and computer control caught up in the optical/near infrared part of the spectrum.

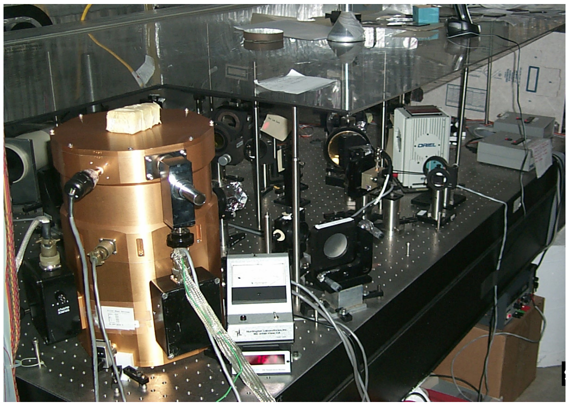


Figure 5. The second optical bench where the science is performed. Note the liquid nitrogen cooled detector (the cylinder on the left).

The final bit of magic occurs on a second optical bench shown in Figure 5. Up to this point the beam of light from the separate telescopes has consisted of the visible and near infrared part of the spectrum. On this optical bench the white light and K band (2.2 microns, near infrared) are separated and follow different paths. The white light from the telescopes are combined and constantly monitored for interference (fringe analysis) and this information feeds back to the carts where the delay lines can be adjusted accordingly. The K bands from the telescopes are combined and finally enter into the detector, a liquid nitrogen cooled CCD chip. The K band light passes through a grating where the K band is split into 5 channels, each of which is analyzed (interferometric spectroscopy!).

Figure 6. The control room where much of the systems are controlled.

It generally requires an hour or so to get everything prepared for a nights observations. Opening the huts and a number of manual alignments must be carried out on the optical benches described above. But most of the systems are controlled from the control room shown in Figure 6.

4. Data Reduction and Analysis

We used the Palomar Testbed Interferometer (Colavita et al. 1999; van Belle et al. 1999) in visibility amplitude mode [K-low or K-high, N-S baseline] to monitor epsilon Aurigae during the winter 2007/08 season on a roughly once per month basis. PTI's K-band “K-low” capability in 5 channels (2.0 to 2.4 microns) presented an exceptional opportunity to precisely measure the angular diameter of the primary star. A high resolution near IR spectrum of epsilon Aur obtained in 2006 January by Dan Clemens at Lowell Observatory shows a bright continuum plus a moderate strength, narrow absorption Brackett gamma line at 2.16 microns in the K band (Clemens et al. 2007). During eclipse, this feature is known to exhibit some variable emission aspects, along with appearance of CO absorption near 2.3 microns (Backman et al. 1985; Hinkle and Simon 1987). Additionally, Spitzer Space Telescope IRS spectra obtained during Cycle 2 (2005-06) show a similarly strong F star continuum and weak IR emission lines of H-alpha and Fe II (Stencel, 2007).

In parallel, eclipse campaign observers, notably Jeff Hopkins and Lothar Schanne (see report at this meeting) are providing excellent UBVJH photometric and H-alpha spectroscopic monitoring of this system, which provide brightness and color information spanning the PTI observations.

In order to obtain accurate visibility readings from the calibration software, one must select bona-fide calibrators (see vanBelle et al. 2008). In addition to having well-known coordinates, proper motion and parallax, calibrators must also meet additional criteria such as being bright enough to be tracked by PTI, while still appearing point-like by nature of size and distance. For a calibrator star to be useful at PTI, an angular diameter less than 1.0 milliarcseconds is desirable (van Belle & van Belle 2005), along with having stable visibility measurements.

Raw data readings are acquired by the interferometer and stored as Level 0 data files. At the end of the observing night, a program processes this data using algorithms (Colavita 1999) to create Level 1 data files that are provided to the end user. Level 1 data consists of fringe and other data that has been corrected for detector bias and then averaged. This data can be provided to the user either as a series of ASCII (space-separated data fields) or FITS files.

Specifically, the Level 1 data files consist of Wide-band visibility squared (“*V^2*”) data, Spectrometer V^2 data, a baseline model, reduction configuration information, an observer log, a nightly report, the catalog (schedule) file, and postscript plots of the wide-band and spectral data. Along with a calibration script and a baseline model (.baseline file), the wide-band (.sum) and spectrometer (.spec) files can be processed by wbCalib and nbCalib in the V2calib package, distributed by the Michelson Science Center (2008), to create a portion of the Level 2 data products, calibrated wide- and narrow-band V^2 data. The two programs are quite particular on the format of input files. Attention to precise formatting of user-generated files is obligatory. If one does not prescribe to the exact formatting as described at the MSC website, even the most verbose error messages may not be helpful. For example, if one creates a calibration script that lists the target star along with its ancillary information on one-line, instead of two, the programs will generate calibrated output without spatial information. Furthermore, the indication of a small syntax error is either no-output from the program or a message indicating that one may have not specified matching calibration scripts and Level 1 data files.

To ensure that the calibrated V^2 data is meaningful, one needs to examine the seeing, jitter and system visibilities. The latter values for calibration stars should range between 0.6 and 0.8 and vary smoothly, to ensure that good diameters have been measured relative to the resolved calibrators. Similarly, the calibrators can be alternatively used as targets to cross-calibrate and verify that one obtains an expected value for a V^2 measurement (i.e. 1.0 for an unresolved calibrator). Finally, if one assumes a particular stellar shape model (see below), one may fit the measured V^2 to the model's visibility function to obtain the diameter of the target star.

The V^2 data for epsilon Aur was fit to a uniform disk ("UD") model, using a first-order Bessel function (approximated using the first-five terms of the power-series expansion), where B is the projected baseline (Gaussian sum of the x and y projections), resulting in the stellar angular diameter in radians, and specific to the wavelength of light at which the data was obtained.

The uniform disk approximation is highly simplified when it comes to stars. The next most realistic assumption is called limb-darkened ("LD"), where the photospheric temperature variation with height causes the edges of the star to be dimmer than the line of sight center. This is clearly seen in solar images, and the center to limb contrast differs among stars. Recent discussions of limb darkening among yellow supergiant Cepheid variable stars (Marengo et al. 2002), suggest effects at the 5% level, less at longer wavelengths, although phase-dependent differences due to pulsation can increase the effect. For our purposes with these "snapshot observations" we will consider the Uniform Disk Diameter (UDD) approximation sufficient for the present interpretation of PTI angular diameter measurements.

5. Discussion and Implications

An interesting, preliminary result of our ensemble of measurements is that the error-weighted uniform disk diameter of epsilon Aurigae at 2.2 microns is 2.35 +/- 0.15 milli-arcseconds (mas). More detailed results are being prepared for publication elsewhere. The PTI result is marginally consistent with the NPOI optical diameter of 2.18 +/- 0.08 mas reported by Nordgren et al. (2001). All of our data are within three sigma of their value, suggesting no long term trends, with one possible exception – 2008 Feb 18 (discussed below). If we adopt the nominal radius of 200 solar radii for the F supergiant (Carroll et al. 1991) at the Hipparcos distance, 625 pc, the implied angular diameter is 3 milliarcsec, somewhat larger than measured. For the Hipparcos distance, our weighted mean UDD suggests a stellar radius of 158 solar radii, more consistent with the discussion by Guinan and Dewarf (2002). The error on the Hipparcos parallax admits a range of distances from 450 to 850 pc (Guinan and Dewarf 2002), which formally admits a range of radii from 114 to 213 solar radii. Next generation astrometric satellites like GAIA will hopefully refine the parallax value.

Naturally, at the end of the observing season, the interferometric data showed peculiarities, possibly correlated with photometric and spectroscopic changes. Hopkins (2008) reported unusual brightening in UBV magnitudes of epsilon Aur during 2008 Feb, overlapping the final session of PTI measurements for the season. We cautiously note an increase in the UDD during that interval of three days. This star has shown 0.4 mag "flare" over the course of hours (see Hopkins et al. – this conference,, and Nha and Lee, 1983), and changes in radial velocity of 1 km/sec per day in the past (a shift from –12 to +19 km/sec during a 30 day interval near mid-eclipse, Struve, Pilans and Zebergs, 1958), so we should be prepared for surprises. Observing conditions could have been better those final nights, but we have to wait for the next observing season to attempt confirmation. The infrared spectra are consistent with the far-UV reported by Ake (2004) and his conclusion that the emission is due to resonance scattering of photons in the expanding wind of the supergiant or disk from an occulted hot source, which is capable of producing the short term variations in light and possibly apparent diameter variations.

Obvious next steps include continued interferometry during coming observing seasons, ideally with imaging interferometry to go beyond uniform disk diameter measurements. An important step in the process involves predicting the disk transit interferometric signal. According to the prevailing model, the 2+ milliarcsecond F star diameter might be expected to bifurcate into a pair of smaller sources of light separated by ~2 milliarcseconds as the dark disk transits, as suggested by our campaign logo [http://www.hposoft.com/Campaign09.html].

We are exploring what manner of interferometric measurement might be expected if this disk eclipse scenario is the case. Using an online 2-D Fourier transform tool (Weber, 2008) helps approximate how the interference pattern might evolve, as shown in the following Figures.

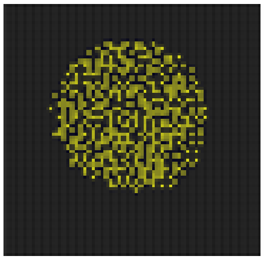
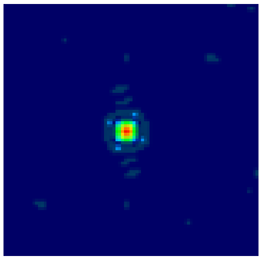


Image 1, July 2009


2D FFT 1

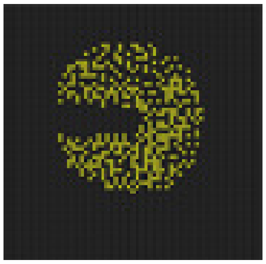
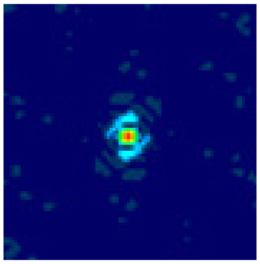


Image 2, Oct.2009


2D FFT 2

The FFT of image 1 is the familiar Airy or diffraction disk seen under ideal seeing conditions. FFTs of images 2 and 3 show the development of bisymmetric but rotating lobes of power that are subject to detection if sufficient u-v plane coverage is possible with existing interferometers.

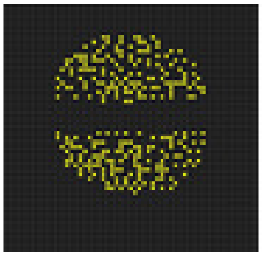
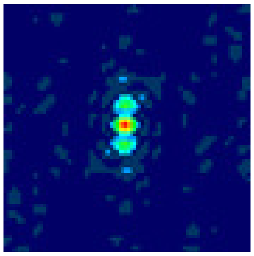


Image 3, 2010


2D FFT

6. Acknowledgements

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For further information, please visit:

http://www.hposoft.com/Campaign09.html

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