Latest Results from the Cambridge Optical Aperture Synthesis Telescope

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Abstract. We present a brief report and discuss progress at the Cambridge Optical Aperture Synthesis Telescope, in particular a number of the current observational programmes. Data from the telescopes are of comparable quality to VLBI arrays with similar numbers of telescopes, and imaging of simple objects has been achieved with dynamic ranges of $\sim 100:1$. These initial results are already beginning to constrain models of cool stars and their atmospheres.

1. COAST - a long baseline optical/near-ir interferometer

Since its first demonstration of synthesis imaging with a separated-element interferometer (Baldwin et al. 1996), our team in Cambridge has been working to exploit COAST as both a test-bed for interferometer design and as a scientific instrument. The essential features of the telescope as of summer 97 are:

- An array comprising 4×40 cm afocal siderostat-fed Cassegrain telescopes in a Y-shaped configuration, with baselines from 2 m to 10 m. A fifth telescope is due to be installed later this year.
- Visibility amplitude and closure phase measurement allowing a full imaging capability at the 10 milliarcsecond level. The beam-combining laboratory has been designed to cope with baselines of up to 100 m, implying possible resolutions of 1 milliarcsecond in the future.
- A 4-way beam-combiner with detectors at optical (650 nm - 1000 nm) and near-infrared (1000 nm - 2500 nm) wavelengths. Operation with either 4 filter-selected wavelength channels or a low-resolution ($R \sim 40$) spectrometer.
- A current sensitivity limit of 8th magnitude in the visible. A near-infrared camera, based on NICMOS technology, will be tested later this season.

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Figure 1. Early views of COAST taken when only 3 telescopes were present and the pipes for feeding the beams into the optics lab had not been installed. The combining lab contains four 25 m long delay lines as well as the optical and near-ir combination and detection systems, and the fast autoguider sensors.

2. Imaging the disks of M giants and supergiants

2.1. Results from monolithic telescopes

A number of existing interferometric studies have shown that surface features on late-type supergiants are potentially commonplace (see, e.g. Buscher et al. 1990; Wilson et al. 1992). While surveys using single large ground-based telescopes

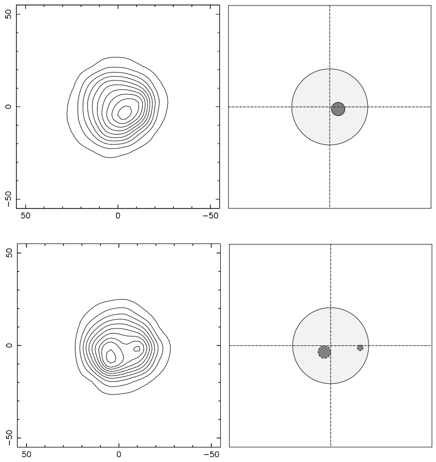

Figure 2. Image reconstructions of α Her at 633 nm obtained in 1992 July (top) and 1993 June (bottom) using interferometry at the WHT (Tuthill et al. 1996). The right-hand panels are representations of the disk plus hotspot(s) model that best fits the measurements. Contours are plotted from 5% to 95% of the peak flux with 10% intervals.

have been successful in discovering such features they have had insufficient spatial resolution to permit a clear understanding of the phenomenon. Measurements with separated-element interferometers will allow observers to address the following questions:

- What are the precise numbers and sizes of the "hotspots"? Are they convective granules or supergranules?
- How large are the temperature excesses associated with them? Are they associated with lower or higher layers in the atmosphere, or perhaps with circumstellar absorption?
- More importantly, what is their relationship to mass loss, variability and envelope structures? Are they responsible for the asymmetric coronal emission seen, for example, in HST images of Betelgeuse (Gilliland & Dupree 1996)?

2.2. Results from COAST

So, how close are we to achieving reliable imaging of resolved stellar disks with COAST? Figure 3 shows one early and a more recent image of two stellar disks obtained with COAST. Though we have not quite reached the quality of imaging

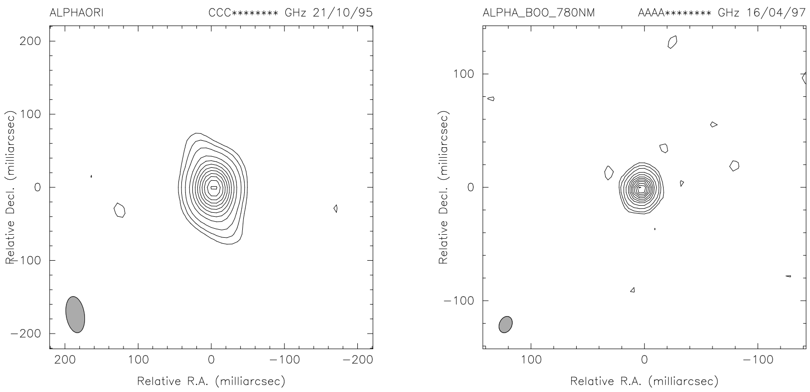

Figure 3. COAST images of Betelgeuse (left) and Arcturus (right). The image of Betelgeuse, obtained at 830nm, shows a featureless circular disk with no surface structure. The apparent ellipticity is an artifact due to the beamshape. At 780 nm, the map of Arcturus shows a somewhat smaller but similarly featureless disk. It was obtained with 4 array elements, and so has a better shaped and smaller beam. In both cases contours are plotted at 2.5, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 99% of the peak intensity.

achieved using interferometric methods on monolithic telescopes, these two maps highlight a number of important points:

- First, that imaging of resolved targets, as opposed to small numbers of point sources, can be routinely achieved.

- Second, that the quality of optical synthesis images is as good as could have been expected. Typically, dynamic ranges of $\sim 100:1$ are achievable, similar to that from a comparable VLBI array. The current limitations are primarily due to calibration uncertainties which will certainly need to be addressed in the future.

- Finally, the images above stress the need for a large number of array elements. The improvement in beam quality in going from 3 telescopes (Betelgeuse) to 4 (Arcturus) is dramatic. As well as improving image quality, larger arrays will also allow rapid imaging in a "snapshot-type" mode.

3. The limb-darkening profile of Betelgeuse

One area of research that has already felt the impact of interferometry is the measurement of stellar limb-darkening (see, e.g. Quirrenbach et al. 1996). In

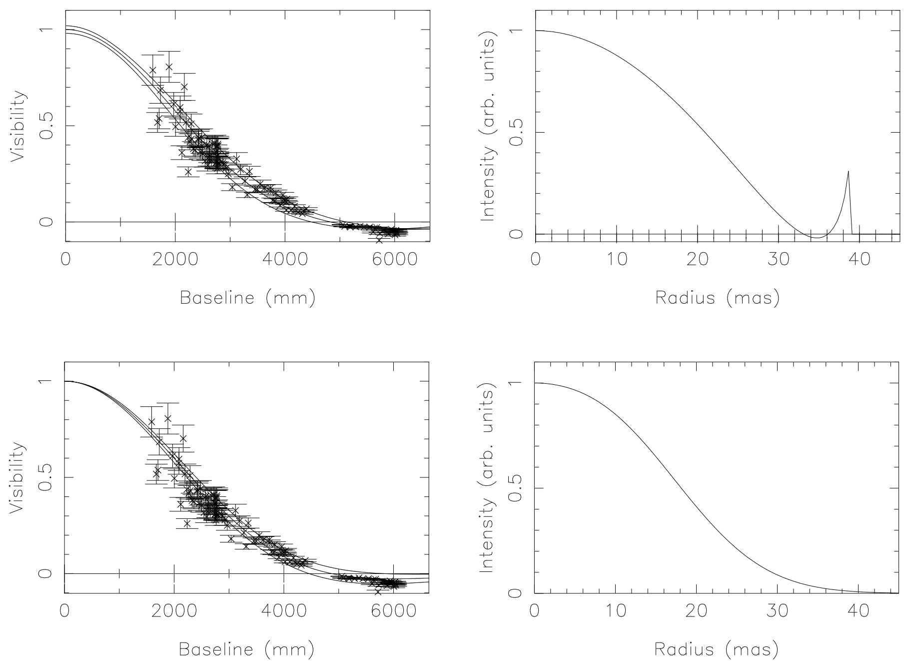

Figure 4. Fits to the observed visibility function of Betelgeuse as measured at 830 nm in 1995 October. Unusually, at this epoch, the star showed no evidence for surface structure and so the centre-to-limb brightness profile of the star could be studied in some detail. The upper and lower panels show the results obtained using a conventional Taylor expansion (top) or a new Gauss-Hermite expansion (bottom). The best-fit model visibility functions are shown at the left, and the implied brightness distributions on the right.

particular, the advent of interferometric arrays offers a new method for studying the strongly wavelength-dependent brightness profiles of cool giants and supergiants.

Recent COAST observations of Betelgeuse, reported by Burns et al. (1997), have identified a new problem relating to the unusual centre-to-limb brightness distribution of the star. Although a reasonable fit to the Fourier data can be achieved using conventional procedures, i.e. by fitting the coefficients of the limb-darkening as expanded in a low-order Taylor form, the resulting image-space model shows non-physical excursions in intensity at the stellar rim.

The problem arises because of the need to include high-order expansion coefficients to reproduce the very large range of intensities in the image profile. Unfortunately, with measurements only up to the second maximum of the visibility function, these high order coefficients cannot be reliably determined. Burns and co-workers have introduced the idea of an alternative Gauss-Hermite expansion which better approximates the type of limb-darkening expected in cooler stellar types. Not only does this reduce the number of parameters needed to describe the data, but it also gives a better fit to them.

4. Detection of radial pulsation in R Leonis

More recently we have been monitoring the apparent diameters of a number of Mira variables. The strong wavelength and time dependence of the apparent sizes of Miras (see, e.g., Scholz and Takeda 1987; Bessell et al. 1989; Bessell et al. 1996) is well know, but has been little studied from an observational point of view.

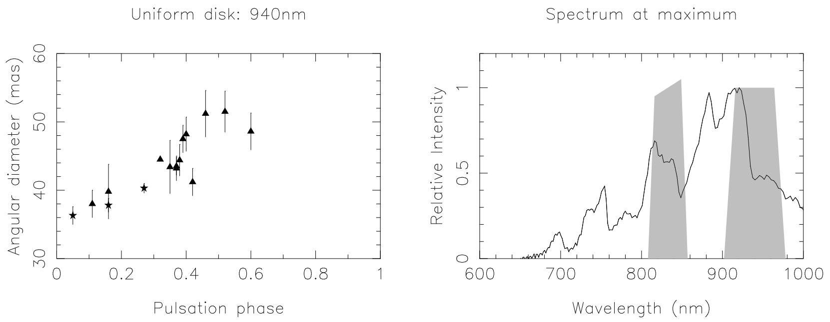

Figure 5. 940 nm uniform disk diameter of R Leonis as measured by COAST over two photometric cycles in 1996-7. The measurements obtained at 830 nm are very similar, and also show a large modulation of comparable magnitude. The filter bandpasses used are shown in the right-hand panel, overlaid on an uncalibrated low-resolution spectrum of the star taken at maximum light.

Data from COAST, obtained over two pulsation cycles for the nearby Mira R Leonis have revealed a large and phase-coherent modulation of the stellar size (Figure 5). Measurements were made at a number of wavelengths, principally in two relatively broad bandpasses (FWHM $\sim$ 45 nm) centred at 940 nm and

830 nm. Estimates of the scale of the stellar emission inferred from both uniform-disk and Gaussian fits to the visibility functions show a similarly sized variation with time, indicating that changes solely in the shape of the limb-darkening function are unlikely to have been the primary cause of the variations seen.

The interpretation of these data is somewhat uncertain, not least because detailed and reliable time-resolved models of the cool pulsating atmosphere of R Leonis are not yet available. Nevertheless, two extreme possibilities can be envisaged:

1. The data represent essentially uncontaminated measurements of the true photospheric radius. In this case both the phase and magnitude of the variation are difficult to understand in the context of current models. The amplitude is far too large and the phase of maximum apparent size should be close to 0.25 (Bessell et al. 1996), not 0.5 as is observed.

2. Alternatively, the observations might be sufficiently affected by the presence of TiO in the filter bandpasses so as to probe changes in the molecular content of the stellar atmosphere and not the true cyclic variations of the photospheric radius.

It is probable that a hybrid situation, in which both expansion and changes in TiO opacity occur as a function of variability phase, best describes the observations. Future measurements, in narrower specific bandpasses, should be able to verify this hypothesis.

5. Conclusions

New data from COAST, together with early results from other optical synthesis arrays (Armstrong et al. 1997), are already beginning to demonstrate the potential of interferometry for cool star research. The number of stars amenable for study, particularly for projected arrays such as the VLTI and Keck Interferometers will run to hundreds. Future developments, for example routine operations in the near infrared and the introduction of spectroscopic capabilities, should open further avenues of research.

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