Astron. Astrophys. 306, L13–L16 (1996)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

The first images from an optical aperture synthesis array: mapping of Capella with COAST at two epochs

J.E. Baldwin[1], M.G. Beckett[2], R.C. Boysen[1], D. Burns[1], D.F. Buscher[3], G.C. Cox[1], C.A. Haniff[1], C.D. Mackay[2], N.S. Nightingale[4], J. Rogers[1], P.A.G. Scheuer[1], T.R. Scott[2], P.G. Tuthill[5], P.J. Warner[1], D.M.A. Wilson[1], and R.W. Wilson[6]

[1] Mullard Radio Astronomy Observatory, Cavendish Laboratory, Madingley Road, Cambridge, CB3 0HE, UK
[2] Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK
[3] Department of Physics, University of Durham, South Road, Durham, DH1 3LE, UK
[4] Minnesota 3M Research Ltd., Pinnacles, Harlow, Essex, CM19 5AE, UK
[5] Space Sceinces Laboratory, University of California at Berkeley, Berkeley, California 94720, USA
[6] Royal Greenwich Observatory, Madingley Road, Cambridge, CB3 0EZ, UK

Received 14 November 1995 / Accepted 12 December 1995

Abstract. We present the first aperture synthesis maps obtained using closure phase techniques with a separated-element optical interferometer. Maps of the double-lined spectroscopic binary Capella (α Aurigae) were obtained at 830 nm with three elements of the Cambridge Optical Aperture Synthesis Telescope (COAST) in September 1995. These maps show clearly the milliarcsecond orbital motion of the system over a 15 day interval. The image quality is comparable to that of VLBI images obtained using similarly sparse radio synthesis arrays, and the location and motion of the binary components are in excellent agreement with the predictions of the latest set of orbital elements. These data demonstrate for the first time the feasibility of operating long-baseline optical/near-infrared interferometers for high-dynamic range high-resolution imaging.

Key words: Techniques: interferometric – Telescopes – binaries: close – Stars: imaging

1. Introduction

The quest for high angular resolution at optical wavelengths has prompted the development of a variety of techniques to overcome atmospheric seeing at astronomical sites. These include speckle interferometry (Labeyrie 1970), triple correlation (Weigelt 1977), optical aperture synthesis (Haniff et al. 1987), adaptive optics (see, for example, Rigaut et al. 1991 and references therein), and, with the advent of the Hubble Space Telescope, satellite observations. Unfortunately these methods, when used on existing single telescopes, are in principle limited to resolutions no better than $\sim$ 10 millarcseconds (mas). While this represents an improvement in resolution by a factor of $\sim$ 40 over that achieved under typical observing conditions, it is still inadequate for many astronomical problems, for example, the surface imaging of main sequence stars and the study of the broad-line regions of nearby active galactic nuclei.

Long-baseline interferometry is the only realistic method for achieving higher resolution. However, the problems associated with operating optical interferometers in the presence of atmospheric turbulence have meant that imaging has not yet been possible with these instruments. Techniques for interferometric imaging have been developed in radio astronomy for cases in which the fringe phases are unstable, and these methods have been vital to the success of very long baseline interferometry (VLBI) and high-frequency synthesis imaging. These "closure" methods (Pearson & Readhead 1984) rely on the simultaneous measurement of triplets of visibilities corresponding to closed triangles of interferometer baselines. The phase of the triple product of these visibilities (i.e. the closure phase) is uncorrupted by antennae-based phase errors. It remains a good observable in the presence of atmospheric turbulence thereby making reliable imaging possible. The extension of these closure methods to optical interferometry has been demonstrated in aperture-masking experiments on the Isaac Newton Telescope (Haniff et al. 1987) and William Herschel Telescope (Buscher et al. 1990) and these techniques are regularly used to give diffraction-limited images of the brightest cool stars (see, for example, Wilson et al. 1992). However, the technical difficulties associated with the application of these methods

Send offprint requests to: J. E. Baldwin to separated-element interferometers have meant that no such implementation has yet been made.

In this paper we report imaging observations of the double-lined spectroscopic binary Capella with the Cambridge Optical Aperture Synthesis Telescope. Our maps are the first true images obtained with any ground-based optical or near-infrared separated-element interferometer. They confirm that high quality diffraction-limited imaging using long-baseline optical arrays is indeed practicable.

2. Observations and data reduction

Observations of Capella were made with the COAST array on the nights of the 13th and 28th September 1995. This instrument, located at the Lord's Bridge Observatory 5 miles west of Cambridge, comprises four 40 cm fixed horizontal afocal Cassegrain telescopes, each fed by a 50 cm siderostat, sending light via alloy pipes into a temperature stabilised laboratory. Within the laboratory various subsystems are responsible for path compensation and fast auto-guiding of the beams from each telescope, as well as beam combination so as to allow measurement of the interference fringes from all pairs of array elements simultaneously. The beam mixing is performed using four 50:50 beam-splitter plates which provide four collimated outputs, each of which contains one quarter of the light from each telescope. Interference between all pairs of telescopes is present in every output. Each is focused onto, and detected by, a separate avalanche photo-diode operating in photon-counting mode. In this arrangement, interference takes place in the pupil plane, and so the optical path in each arm of the interferometer is modulated by about 50 μm in order to scan the fringes past each photo-diode. Further details of the design and operation of COAST can be found in Baldwin et al. (1994a,b).

For the experiments reported here, three of the four COAST telescopes were employed, each stopped down to 14 cm to provide a good match to the local seeing conditions. The telescopes were arranged in a close-packed configuration giving a maximum baseline of ~ 6.1 m, and allowing simultaneous measurements of three visibilities and one closure phase. The observations of Capella were interleaved with observations of ι Aurigae which, with a diameter of 7 mas (Benson et al. 1991), is only marginally resolved on our longest baseline. Data were collected over a 5 hour period on each night so as to give sufficient coverage of the uv-plane for mapping (see Fig. 1). Further details of the observations are given in Table 1.

For measurements of fringe amplitudes, observations were made on each baseline separately. The visibility amplitudes, V, were derived by Fourier transforming segments of the data stream corresponding to single sweeps of the fringe packet across the detector. Mean power spectra with high signal-to-noise (10^2–10^4) were then obtained by averaging over 99 second sequences of data. The resulting spectra showed a peak centred at the mean scan rate of

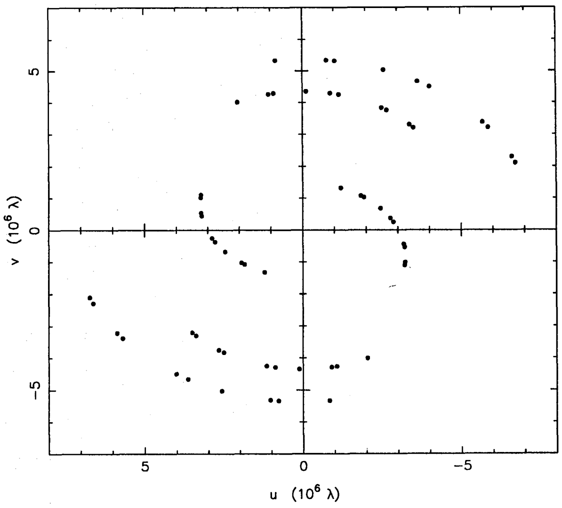

Fig. 1. uv-plane coverage for the observations of the 13th September 1995. Each point corresponds to an individual visibility datum calculated from 99 seconds of raw data. At the wavelength of observation, $10^6\ \lambda$ corresponds to a baseline of 0.83 m

Table 1. Observing log

Night	13/09/95	28/09/95
Pupil size (cm)	14	14
$\lambda/\delta\lambda$ (nm)	830/40	830/40
Seeing (arcseconds)[a]	1.4	1.6
Coherence time (milliseconds)[b]	7.5	2.3
Total No. uv measurements	30	24
Photon rate/telescope (s^{-1})	1.2×10^6	9.4×10^5
Total observing time (s)	6600	6200

[a] At a mean wavelength of 600 nm
[b] At 830 nm

the fringes, 715 Hz for these observations, superposed on a "white" background attributable to photon noise. The area under this peak above the background noise power, normalized by the mean photon rate squared, was used to estimate the mean squared fringe visibility for each sequence of data. This quantity was computed for Capella and ι Aurigae, and their ratio, corrected for the finite size of the calibrator, averaged over the four detectors to give the adopted value of $\langle V^2 \rangle$. The final visibility amplitudes had errors in the range 5% to 10%, their quality being limited primarily by calibration.

In order to make closure phase measurements, the modulations of the optical paths were chosen so that the scan rates of the fringes from the three baselines were 238, 477, and 715 Hz. Beams from all of the array elements were combined so that data for all three baselines could be recorded simultaneously. The closure phases were derived by first dividing the data into short sequences of either 4.2

or 8.4 ms ($\simeq$ the atmospheric coherence time). The complex visibilities on the three interferometer baselines were then calculated for each of these segments, and their triple product computed and averaged over 99 seconds of data. After correction for photon noise, the argument of the mean triple product then gave the closure phase. Values were derived from all four output channels of the interferometer, and their mean taken. Typical errors on the closure phases were $\pm 2°$. Data from the calibrator, for which the closure phases were expected to be zero, gave values of $0° \pm 2°$, indicating only a small level of crosstalk between the three baselines and a low level of systematic error.

3. Results and discussion

The primary results of our study are the two images of Capella displayed in Fig. 2. These were reconstructed from the measured visibility amplitudes and closure phases using 10 iterations of self-calibration within the Caltech VLBI mapping package. In each case, the initial starting model was a circularly symmetric Gaussian. For clarity each map has been restored with a circularly symmetric 20 mas beam, although the actual *uv* coverage corresponds to an elliptical beamshape of 30 × 18 mas in position angle 53°. Both maps clearly resolve the 50 mas binary, and together show the rapid change of the system over the 15 day interval between observations. Importantly, neither image shows any evidence of a spurious symmetric counter-companion, as would have been expected if the Fourier phase data had been unreliable. The noise features on the map are less than 5% of the peak flux. This is consistent with the number and quality of the visibility data used to generate the images, on the basis of which a dynamic range of approximately 50 would have been expected (i.e. the square root of the number of *uv* data divided by the fractional error in the visibilities). On both nights the measured visibility data were in excellent agreement with the visibility functions of the reconstructed images (see, for example, Fig. 3), despite the small number of data points.

The most recent study of the Capella system relevant to the observations reported here is that of Hummel et al. (1994). Using visibility amplitude data from the MKIII interferometer, they re-determined the orbital elements of the system, and also estimated a magnitude difference between the Aa and Ab components of $-0^m.05 \pm 0^m.05$ at 800 nm. Our own images confirm their estimate, giving a flux ratio of 0.9 : 1 at the longer wavelength of 830 nm. Fig. 4 shows the predicted positions, based on these orbital elements, together with our measurements. These maps are entirely consistent with the orbital predictions, but do not yet have small enough errors to constrain the orbital elements in any new sense. Longer baselines, and an improved mapping algorithm that incorporates corrections for orbital motion during the observations, should reduce these errors significantly.

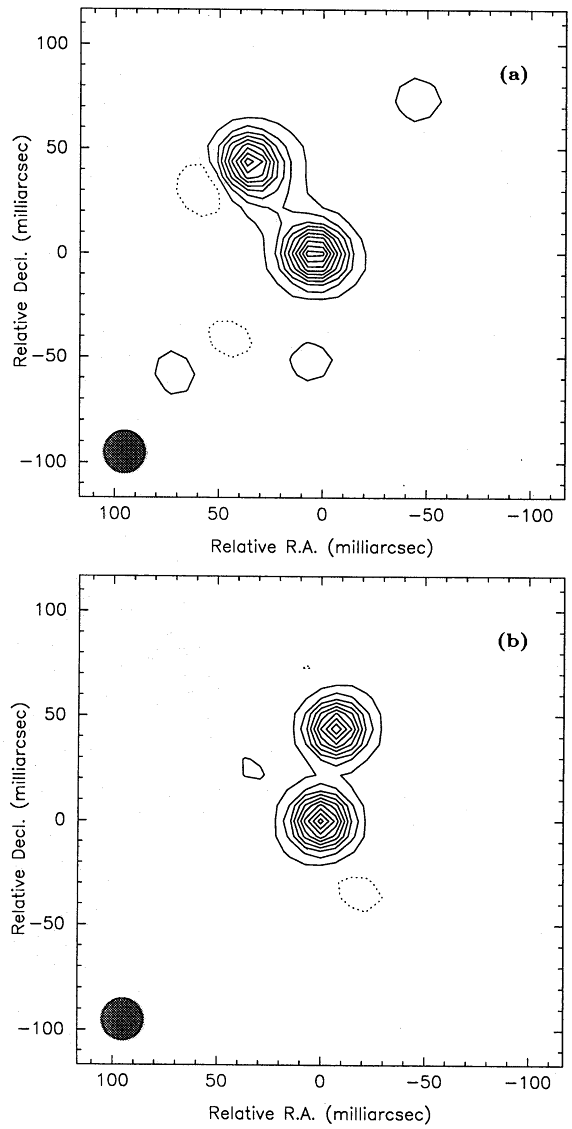

Fig. 2. Image reconstructions of Capella, from data obtained on the nights of the 13th (a) and 28th (b) September 1995. In each plot the contour levels are plotted from -5% to 95% of the peak flux with an interval of 10%. North is to the top and East to the left. The 20 mas restoring beam is shown in the bottom left of each panel. Note that because of the *uv* plane coverage, the image resolution is lower in PA 53° than along the perpendicular direction

4. Conclusions

We have presented the first true images from an interferometric array of optical telescopes. Their quality, and close agreement with the predictions of an independent model of the source, show the reliability of the techniques used, which offer the realistic prospect of application to a wide range of astronomical problems.

Acknowledgements. The development of COAST would not have been possible without the assistance of numerous tech-

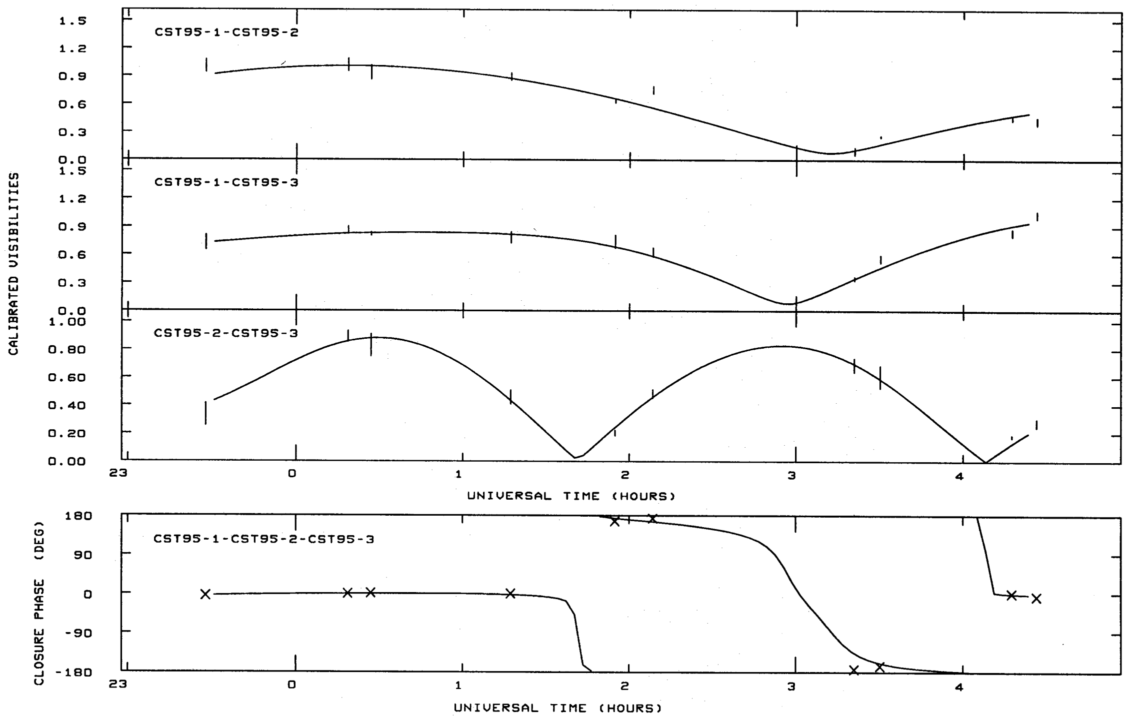

Fig. 3. Visibility data for the night of 13th September 1995. The model curve corresponds to the image reproduced in Fig. 2(a)

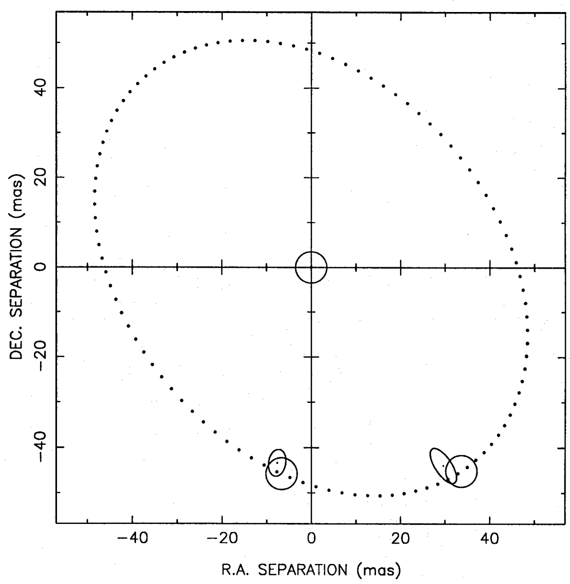

Fig. 4. Predicted and observed locations of Capella based on the observations reported here and the interferometrically determined orbit of Hummell at al. (1994). The circular markers represent the angular size of the individual components, while the elliptical contours are error ellipses for the measurements reported here. The point markers are placed at one day intervals

nical and support staff at the Cavendish Laboratory and at Lord's Bridge Observatory. It is a pleasure to thank them all for their tireless effort over the past five years. We are grateful to the Royal Society (CAH), the Isaac Newton Studentship Fund (TRS), and the C.T. Taylor Fund (TRS) for financial support. We thank SERC and PPARC for supporting the construction and operation of COAST.

References

Baldwin J.E., Boysen R.C., Cox G.C. et al., 1994a, Proc. S.P.I.E, 2200, 112

Baldwin J.E., Boysen R.C., Cox G.C. et al., 1994b, Proc. S.P.I.E, 2200, 118

Benson J.A., Dyck H.M., Ridgway S.T. et al., 1991, AJ, 102, 2091

Buscher D.F., Haniff C.A., Baldwin J.E., Warner P.J., 1990, MNRAS, 245, 7p

Haniff C.A., Mackay C.D., Titterington D.J. et al., 1987, Nat, 328, 694

Hummel C.A., Armstrong J.T., Quirrenbach A. et al., 1994, AJ, 107, 1859

Labeyrie A., 1970, A&A 6, 85

Pearson T.J., Readhead A.C.S., 1984, ARA&A, 22, 97

Rigaut F., Rousset G., Kern P. et al., 1991, A&A, 250, 280

Weigelt G., 1977, Opt. Comm. 21, 55

Wilson R.W., Baldwin J.E., Buscher D.F., Warner P.J., 1992, MNRAS, 257, 369

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.