MEASURING STARS WITH HIGH ANGULAR RESOLUTION: RESULTS FROM NARRABRI OBSERVATORY

R. Hanbury Brown

Chatterton Astronomy Department
University of Sydney

ABSTRACT. The stellar intensity interferometer at Narrabri Observatory was used to measure the angular diameters of 32 stars in the spectral range 05f to F8 and brighter than about V = +2.6. The results were combined with measurements of absolute flux and, in a few cases parallax, to find the emergent flux, effective temperature, radius and luminosity of the stars. The methods used to calibrate these measurements and their uncertainties are discussed. It is shown that in measuring emergent flux and effective temperature the major uncertainties were most frequently in the measurements of angular size.

1. INTRODUCTION

The stellar intensity interferometer at Narrabri Observatory (Hanbury Brown et al. 1967a,b, Hanbury Brown 1974) consisted of two large mosaic reflectors (6.7m in diameter) mounted on trucks which moved around a circular railway track 188 m in diameter. The reflectors were controlled by a computer assisted by automatic photoelectric star-guiding; they followed a star in azimuth by moving around the track, and in elevation by tilting about a horizontal axis. The separation between the reflectors, the baseline, could be pre-set anywhere in the range 10-188 m and their movement was controlled so that this baseline was always normal to the direction of the star. At the focus of each reflector the light from the star passed through a narrow-band (~ 10 nm) interference filter and was then focussed on to the cathode of a photomultiplier. High-frequency (10-100 MHz) fluctuations in the anode currents of these photomultipliers were carried by cables to a central control building where the time-average of their cross-product, or *correlation*, was measured in an electronic correlator. The angular diameter of a star was found by measuring this correlation c(d) as a function of the baseline length, d.

The principal programme of the Observatory was to measure the angular diameters of 32 stars in the spectral range 05f to F8 and with magnitudes brighter than V = +2.6. This program took 6 years to carry out (May 1965-February 1972).

D. S. Hayes et al. (eds.), Calibration of Fundamental Stellar Quantities, 185–192.

https://doi.org/10.1017/S0074180900078840 Published online by Cambridge University Press

2. DATA REDUCTION

2.1 Correcting for Zero-drift of the Electronic Correlator

One of the most difficult technical problems in developing the stellar intensity interferometer in the early 1960's was to reduce the zero-drift in the output of the electronic correlator. This zero-drift was monitored as follows. In the intervals between observations the phototubes were illuminated by small lamps which were adjusted to give exactly the same light flux as the star. The light from these two lamps was completely uncorrelated and so the mean output of the correlator was a measure of the zero-drift. Experience showed that this drift did not change significantly over a period of 3 days and so the observed correlation $\overline{c(d)}$ from a star was corrected by an amount $\overline{D}$ equal to the mean rate of zero-drift for a period of 1½ days before and after the observation, to find the corrected value of correlation $\overline{c_o(d)}$, where

$$\overline{c_o(d)} = \overline{c(d)} - \overline{D} \qquad (1)$$

2.2 Normalizing the Observed Correlation for Variations of Gain and Light Flux

The measured values of correlation were normalised for variations in the gain of the correlator and phototubes and in the light flux from the star as follows. The gain of the correlator (G) was measured before and after every night's observation with an uncertainty of 1 per cent. The measured values of correlation together with the two phototube anode currents were printed out by the correlator every 100 s.

The final mean value of correlation $\overline{c_N(d)}$, for a 100 s observation, weighted by the square of the signal/noise ratio in each observation, and normalized for variations in the gain of the phototubes and correlator was found from,

$$\overline{c_N(d)} = \overline{c_o(d)}/(G) \;.\; \overline{i_1,\, i_2} \qquad (2)$$

where i_1, i_2 are the mean phototube anode currents due to the star, found by subtracting from the total observed anode currents the components due to the night sky and moon light. Near new moon these corrections were about 1 per cent for stars of magnitude +1 and were never allowed to exceed 10 per cent.

2.3 Uncertainty in the Normalised Correlation

The principal source of uncertainty in the normalized correlation was the statistical fluctuation (noise) in the output of the correlator. This uncertainty had two components, the uncertainty in the mean correlator output $\overline{c(d)}$ during the actual run on the star and the uncertainty in the measured value of $\overline{D}$ the mean drift. Both of the uncertainties were found by statistical analysis of the 100 s observa-

https://doi.org/10.1017/S0074180900078840 Published online by Cambridge University Press

tions and were combined to find the final uncertainty in the normalized correlation $\overline{c_N(d)}$.

There were a number of other minor uncertainties which were taken into account. These included possible small losses of correlation due to misalignment of the baseline and uncertainties in the measurement of the phototube anode currents and correlator gain. Finally we allowed for the possibility that there were unknown sources of unwanted correlation from the night sky, for example, due to Cerenkov radiation from cosmic rays. To set limits to any such false correlation we observed the bright star β Crucis for 55 hours with a baseline (154 m), so long that any correlation due to the star itself would have been negligible. No significant correlation was observed. We also exposed the instrument to areas of sky without any bright stars and, again, no significant correlation was observed.

The overall uncertainty in the final value of normalized correlation was found by combining all these uncertainties as though they were random and statistically independent.

2.4 The Determination of Angular Diameter

It can be shown that the correlation $\overline{c_N(d)}$ varies with the length of the baseline (d) as,

$$C_N(d) \propto \Delta_\lambda \, \Gamma_\lambda^2(d) \qquad (3)$$

where Δ_λ is the *partial coherence factor* and takes account of the fact that stars of large angular diameter are partially resolved by the very large reflectors themselves. The *correlation factor* $\Gamma_\lambda^2(d)$ is a function of the angular size θ of the star, and the effective wavelength of the light λ and the baseline length d; for a circular disc of uniform surface brightness and angular diameter θ_{UD} it is given by,

$$\Gamma_\lambda^2(d) = 2[J_1(x)/x]^2 \qquad (4)$$

where $x = \pi d\theta_{UD}/\lambda_o$ and it is assumed that θ_{UD} is so small that $\Delta_\lambda \approx 1$. For a limb-darkened star the shape of this theoretical curve is not significantly altered, although the scale is changed.

For each baseline the final value of mean correlation was found by combining the observations on different nights weighted according to the square of their signal/noise ratios. A curve was then fitted to these points using a computer. For most stars, where $\Delta_\lambda \approx 1$, this curve was given by equation (4), but for some stars with larger angular sizes the observed points were fitted to a theoretical curve using equation (3). The results of this analysis gave the correlation at zero-baseline $\overline{c_N(0)}$ and the angular diameter of the equivalent uniform disc θ_{UD} together with their r.m.s. uncertainties. The final uncertainties in both $\overline{c_N(0)}$ and θ_{UD} took into account the uncertainties in fitting the observations to a theoretical curve and included the uncertainties in the zero-level of the correlator.

These values of θ_{UD} (the angular diameter of an equivalent uniform disc) were then corrected for limb-darkening to find θ_{LD} the true angular diameter for each star. The ratio θ_{LD}/θ_{UD} was computed for each star by comparing the intensity distribution across the disc of the star, as predicted by an appropriate model atmosphere, with the intensity distribution for an uniform disc. The correction factor for limb-darkening was small and had a mean value of about 4 per cent; the uncertainties in this factor introduced an additional uncertainty into the final true angular diameter of about 0.5 per cent.

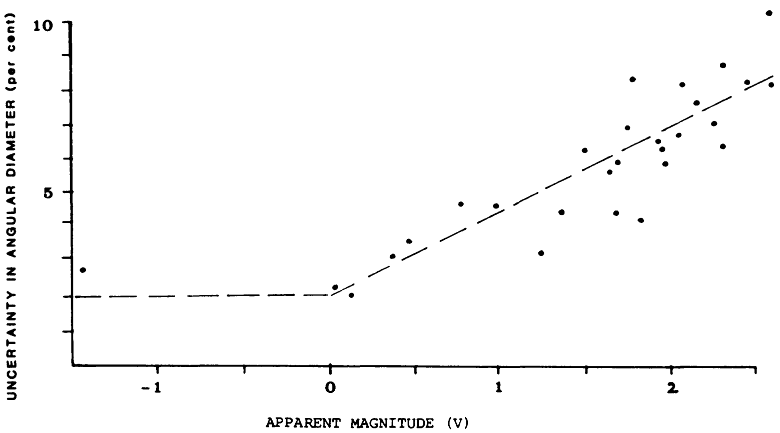

Fig. 1. The uncertainty ($\sigma\theta_{LD}$) in the measured values of angular diameter as a function of the apparent (V) magnitude of the 32 stars.

2.5 Uncertainties in the Final Angular Diameters

Fig. 1 shows the final uncertainties ($\sigma\theta_{LD}$) in the measured angular diameters of the 32 stars as a function of their apparent V magnitudes. Three of the stars have been omitted from this diagram (α Car, δ CMa, γ Vel) because they presented special problems. The broken line suggests the "average" relationship between uncertainty and apparent magnitude. The results are scattered about this line because, for any one star, the uncertainty is not a simple function of brightness but also depends on spectral type and on the length of time for which the star was observed. Most of the exposures lay in the range 40 h for the brighter stars, to a maximum of 120 h for the fainter stars. The figure shows that for stars brighter than about V = 0 the uncertainty did not decrease but remained constant at about 2 per cent. It was determined by the combined uncertainties in, the gain of the correlator (~ 1½ per cent), the photo-tube anode currents (~ 1 per cent), mis-alignment of the base-line (< 1 per cent) and in the corrections for limb-darkening (~ 0.5 per cent). These errors were taken to be random and statistically independent and did not, as far as we could find, introduce any significant systematic errors into the measurement of

https://doi.org/10.1017/S0074180900078840 Published online by Cambridge University Press

angular size.

For stars fainter than V = 0 the uncertainty increased and was largely due to the combined effects of the statistical fluctuations (noise) and zero-drift in the output of the electronic correlator. It was a function of brightness and increased from 2 per cent at V = 0 to about 8 per cent at V = +2.5.

3. INTERPRETATION OF RESULTS

3.1 The Detection of Multiple Stars

In finding the properties of these 32 stars it was important to know whether or not any particular star was single or multiple. It was not always possible to find this out from the existing optical evidence, because the interferometer was capable of resolving binary or multiple stars that had not previously been detected. If a star is binary, and if the angular separation of the two components is resolved at the shortest basline, the apparent value of the zero-baseline correlation $c_N(0)$ will be reduced relative to that expected from a single star of the same total brightness by the factor,

$$(I_1^2 + I_2^2)/(I_1 + I_2)^2 \qquad (5)$$

where I_1 and I_2 are the intensities of the two components, and it is assumed that the individual stars are themselves unresolved.

For 27 of the 32 stars measured in this program, the measured value of $c_N(0)$ was not significantly less than unity, which implied that any companion stars which they might have were at least 2.5 magnitudes fainter. It follows that any correlation due to such companions was less than 1 per cent of that from the bright stars themselves, and could not have introduced significant errors into the measurements of angular size. Five of the stars were clearly multiple, and their values of $c_N(0)$ were used to estimate the brightness of their companions. While these companions did not introduce appreciable errors into the measurements of angular size, their presence had to be taken into account in finding emergent fluxes and effective temperatures.

In the case of one binary star (α Vir) we made an elaborate series of observations (Herbison-Evans et al. 1971) which, when combined with spectroscopic data, yielded all the parameters of the orbit including the inclination, eccentricity and angular size of the semi-major axis. They also yielded the brightness ratio of the two components, the emergent flux, the effective temperature and the luminosity of the primary component. An interesting feature of this work was that the distance of the star (84±4 pc) was found by combining the measured values of the physical size and angular diameter of the semi-major axis.

3.2 Finding the Emergent Fluxes and Effective Temperatures

The emergent flux (F) at the surface of a star is related to the integrated flux (f) outside the Earth's atmosphere by,

https://doi.org/10.1017/S0074180900078840 Published online by Cambridge University Press

$$F = 4f/\theta_{LD}^2 \qquad (6)$$

The measurement of these integrated fluxes is discussed in detail by Code et al. (1976). Briefly, they were found by integrating the flux found in 5 wavelength bands extending from the ultra-violet to the infra-red. Measurements of the ultra-violet flux in the range 110-350 nm were carried out by the satellite observatory OAO-2, and were calibrated by Aerobee rocket flights and synchrotron radiation from the University of Wisconsin electron storage ring. Measurements in the range 330-808 nm were carried out by Davis and Webb (1974) using ground-based telescopes, and were calibrated in absolute units by reference to the absolute spectrophotometry of α Lyr by Oke and Schild (1970). Measurements at wavelengths greater than 808 nm were taken from the infra-red photometry of Mitchell and Johnson (1969) and Johnson et al. (1966) and were also calibrated by the absolute spectrophotometry of Oke and Schild (1970).

For stars of spectral type earlier than B3 the integrated flux was corrected for the absence of observations at wavelengths shorter than 110 nm by using the LTE statistically blanketed models of Kurucz et al. (1972). A generous estimate of the uncertainty in this correction was made: 20 per cent for $T_e < 25\,000$ K and 50 per cent for $T_e > 25\,000$ K.

Two other corrections were made to the integrated fluxes. Firstly, the values for 5 stars in our list were corrected for the presence of companions; the largest correction was 21 per cent (γ Vel). The integrated fluxes were also corrected for extinction which was significant for only 10 of the stars; the color excesses for these stars, together with the extinction curve, is given by Code et al. (1976).

The effective temperature of a star (T_e) is defined by,

$$T_e = (F/\sigma)^{\frac{1}{4}} \qquad (7)$$

where σ is the Stefan-Boltzmann constant. The effective temperatures of the 32 stars were calculated from this equation using the final values of the integrated flux (F).

3.3 Uncertainties in the Emergent Fluxes and Effective Temperatures

Fig. 2(a) is a histogram of the uncertainties in the final values of effective temperature (T_e) for the 32 stars. From equation (7) it can be seen that they are compounded of the uncertainties in the measured values of angular diameter ($\sigma\theta_{LD}/2$) and in the measured values of integrated flux ($\sigma f/4$). Fig. 2(b) illustrates the relative contributions by these two quantities to the final uncertainty in F. It shows that for the majority of stars, 20 out of 32, the major contribution to the uncertainty in T_e, and hence of F, was due to the measurements of angular size. However, for 11 of the stars the major uncertainty was due to the measurements of integrated flux. All of these 11 stars were of spectral type earlier than AO, and this results reflects the difficulty of measuring the integrated flux of very hot stars.

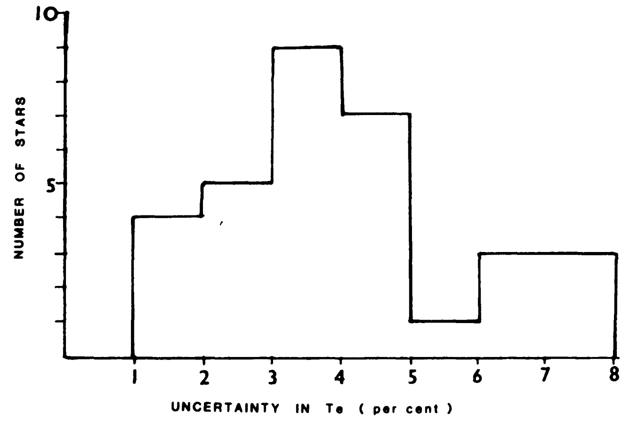

Fig. 2(a) The distribution of the uncertainties in the effective temperatures (T_e) of the 32 stars.

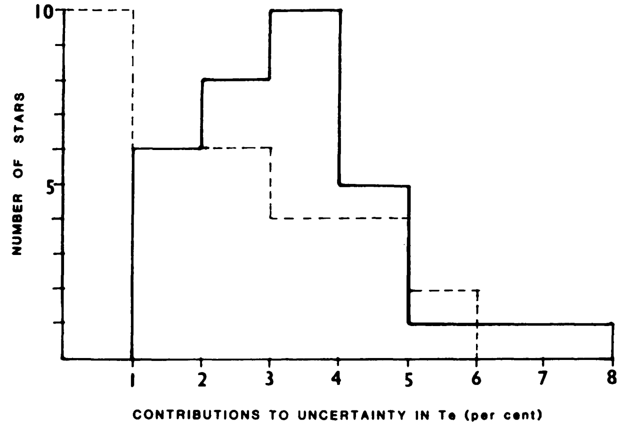

Fig. 2(b) A comparison of the contributions to the uncertainties in the effective temperatures (T_e) due to uncertainties: (solid line) in the angular diameters ($\sigma\theta_{LD}/2$): (broken line) in the integrated fluxes ($\sigma f/4$).

It should be noted that the measurements of F and T_e are wholly empirical with two qualifications. Firstly, model atmospheres were used to make small corrections for limb-darkening. Secondly, for the hottest stars the flux at wavelengths shorter than 110 nm was estimated using model atmospheres. For most stars this use of models accounted for only small corrections.

3.4 Stellar Luminosities and Radii

Only 12 of 32 stars have reliable trigonometrical parallaxes while the distance of α Vir was found, as we have already noted, in a separate program. For these 13 stars it was possible to compute luminosities and radii. For 10 of the stars the uncertainty in the trigonometric parallax was significantly greater than that in the measured angular size. Thus the uncertainties in the radii and luminosities of these stars were due, predominantly, to the large uncertainties in their parallaxes.

4. CONCLUSION

The Stellar Intensity Interferometer at Narrabri Observatory was used to measure the apparent angular diameters of 32 stars brighter than V = +2.6 in the spectral range 05f to F8. These measurements were combined with measurements of integrated flux to find the emergent fluxes and effective temperatures of these stars. The resulting values are almost wholly empirical, only minor corrections having been made by using model atmospheres. It is interesting to note that, for the majority of these stars, the accuracy of the emergent flux and effective temperature, found in this way, was limited by the uncertainties in the measurement of angular size.

The results were also used to find the radius and luminosity of the few stars for which there are reasonable trigonometrical parallaxes. For almost all these stars the accuracy of the final result was limited by the uncertainty in the trigonometrical parallax.

REFERENCES

Code, A.D., Davis, J., Bless, R.C. and Hanbury Brown, R. 1976, Astrophys.J., **203**, 417.

Hanbury Brown, R. 1974, The Intensity Interferometer, (Taylor and Francis, London).

Hanbury Brown, R., Davis, J. and Allen, L.R. 1967a, Mon. Not. R. Astron. Soc., **137**, 375.

____________ 1967b, ibid., **137**, 393.

Herbison-Evans, D., Hanbury Brown, R., Davis, J. and Allen, L.R. 1971, Mon. Not. R. Astron. Soc., **151**, 161.

Johnson, H.L., Mitchell, R.I., Iriarte, B. and Wisniewski, W.Z. 1966, Comm. Lunar and Planet. Lab., **4**, 99.

Kurucz, R.L., Peytremann, E. and Avrett, E.H. 1972, Blanketed Model Atmospheres for Early Type Stars. (Smithsonian Press, Washington, D.C.).

Mitchell, R.I. and Johnson, H.L. 1969, Comm. Lunar and Planet. Lab., **8**, 1.

Oke, J.B. and Schild, R.E. 1970, Astrophys. J., **161**, 1015.

Discussion of this paper occurred after the paper by McAlister.