STELLAR DIAMETERS, LIMB DARKENING, EXTENDED ATMOSPHERES, AND SHELLS: OBSERVATIONS WITH THE MKIII INTERFEROMETER

A. QUIRRENBACH
NRL/USNO Optical Interferometer Project and USRA

1. Introduction

The resolution of close binaries and direct measurements of stellar angular diameters were the first achievements of astronomical interferometry (Michelson and Pease 1921). Fringe tracking interferometers are now capable of producing visibility measurements which are sufficiently sensitive and well-calibrated to make more sophisticated measurements possible. Results from current instruments include measurements of limb darkening, of the wavelength-dependence of stellar diameters, and of non-spherical stars, and observations with narrow spectral bands. This paper summarizes recent results from the MkIII interferometer[1], concentrating on single stars and their envelopes. More detailed descriptions of the instrument and the data reduction procedures are given by Mozurkewich et al. (1991).

2. Angular Diameter Measurements

Measurements of stellar diameters with the MkIII interferometer have been presented by Hutter et al. (1989), Mozurkewich et al. (1991), and Quirrenbach (1992a). At 800 nm, 50 stars have been measured with formal errors $\leq 3\%$; for 10 stars the errors are $\leq 1\%$. At 550 nm, 27 stars have formal errors $\leq 3\%$. The key to precise measurements of stellar angular diameters is very careful calibration of the visibility data. The agreement of our results with diameters obtained with the infrared flux method, from lunar occultations, and from other interferometric measurements is quite good; systematic offsets might be present on the $\sim 3\%$ level, however.

3. Limb Darkening of Arcturus

The equivalent uniform disk diameter of any given star varies with wavelength, since the amount of limb darkening depends on wavelength. Comparison of the measured stellar diameters at two wavelengths gives therefore indirect information on limb darkening (Mozurkewich et al. 1991). In contrast, the direct measurement of limb darkening with Michelson interferometers is difficult, since the difference between a limb darkened disk and a somewhat smaller uniform disk is significant only beyond the first null of the visibility function, where fringe contrast and signal-to-noise ratio are low. With the MkIII interferometer, this problem can be partly circumvented by taking data in blue channels, while fringes are tracked in the red. Observations of

[1] The MkIII Optical Interferometer located on Mt. Wilson, CA, is jointly operated by the Center for Advanced Space Sensing of the Naval Research Laboratory (NRL) and the U.S. Naval Observatory (USNO).

J.G. Robertson and W.J. Tango (eds.), Very High Angular Resolution Imaging, 407–409.

https://doi.org/10.1017/S0074180900010806X Published online by Cambridge University Press

Arcturus (α Boo) at 550 nm close to the null of the visibility function gave a fringe contrast of only $V^2 = 2\cdot10^{-5}\pm2\cdot10^{-4}$; this is probably the lowest upper limit of V^2 ever measured. Data at even longer baselines are clearly inconsistent with a uniform disk, but can be fitted with a $\sim$ 85% linearly limb darkened disk. Together with the measurements of Sirius with the Narrabri intensity interferometer by Hanbury Brown et al. (1974), these are the only direct measurements of limb darkening for stars other than the sun.

4. Atmospheric Extension of Cool Giant Stars

In cool giant and supergiant stars, the radius where the atmosphere becomes opaque, and therefore the observable stellar diameter, depends on the TiO absorption strength; it is therefore wavelength-dependent. To study this effect quantitatively, a sample of cool stars was observed with two filters matched to the deep TiO absorption band at 712 nm and the relatively uncontaminated continuum at 754 nm. Stars with spectral types K5III or M0III have the same diameters in both filters, whereas cooler stars (M3III to M5III) appear to be $\sim$ 10% larger at 712 than at 754 nm (Quirrenbach et al. 1993). The diameter ratio is even larger for supergiant stars. Reliable data on 40 stars have been obtained so far; the error for the 712/754 nm diameter ratio is typically $\sim$ 3%. Detailed observations of Mira (o Ceti) at 800 nm in the fall of 1990 showed that this star is not circularly symmetric, that its size changes with phase, and that the position angle of the asymmetry varies by tens of degrees on the time scale of a month (Quirrenbach et al. 1992). These findings can be interpreted in terms of nonradial pulsations.

5. Nova Cygni 1992

The bright ($V_{\max} \approx 4.4$) Nova Cygni 1992 was observed with the 19.6 m baseline on February 28 and 29, approximately 10 days after maximum light (Quirrenbach 1992b). A combined fit to the data at 500, 550, and 800 nm gives a uniform disk diameter of 3.8 mas. Data were also taken in a 10 nm wide filter center on the Hα line at 656 nm. The uniform disk diameter in this filter was 5.1 mas. Combining this diameter with an estimate of the expansion velocity from spectroscopic data, the distance to the Nova can be derived. Assuming a velocity in the range 1000 to 1300 km s^{-1}, the distance is between 2.2 and 2.9 kpc. There are, however, several systematic uncertainties in these values, most importantly the fact that we cannot disentangle the contributions of the optically thick photosphere, optically thin continuum, and line radiation to the emission in our bandpass. M_V at maximum brightness, estimated from the light curve's rate of decline, was ~ -7.7. Together with a differential extinction between 0.2 and 0.8 mag kpc^{-1}, this gives a distance range from 1.3 to 2.5 kpc, in good agreement with the above completely independent estimate.

6. Be Stars

Seven Be stars (γ Cas, ϕ Per, ψ Per, η Tau, 48 Per, ζ Tau, and β CMi) were observed in the fall of 1992 with baseline lengths ranging from 4 to 31.5 m. Data were taken in a 1 nm wide filter centered on the Hα line and in a continuum filter at 550 nm. All target stars are virtually unresolved in the continuum, but well resolved in the line. The visibility variations with hour angle of several stars are clearly inconsistent with spherically symmetric models. Preliminary fits with elliptical Gaussian models indicate major axes in the range of ~ 1.5 mas (for β CMi) to ~ 2.9 mas (for γ Cas) and axial ratios between ~ 0.22 (for ζ Tau) and ~ 1 (for η Tau). The fitted values for the axial ratios may in some cases be upper limits, because the sources may be unresolved along the minor axis. For ψ Per we obtain a position angle, which agrees with the one measured by Dougherty and Taylor (1992) in the radio regime on a ~ 40 times larger scale.

7. Conclusion

Long-baseline interferometry with independent telescopes has made enormous progress since its first demonstration by Labeyrie (1975). A few years ago, the detection of fringes and the resolution of stars were considered major accomplishments. In contrast, today it is possible to show that the images of stars are not perfectly circular disks with uniform brightness and wavelength-independent radii, as illustrated above. With the GI2T instrument, variations of visibility amplitude and phase across the Hα line in γ Cas have been measured (Mourard et al. 1989). The next generation of optical interferometers will measure closure phase and thus produce true images of stellar photospheres and envelopes. Novae and Be stars appear to be particularly promising targets, since spectrally resolved maps of the Hα line will give unprecedented information about the shell dynamics. Further increases in sensitivity and advances in detector technology (especially in the infrared) will bring new classes of objects within reach of optical interferometers. Within a few years, interferometry will evolve from a "fringe science" to a fully integrated tool of mainstream stellar astrophysics.

Acknowledgements

This work has been done in collaboration with Drs. J.T. Armstrong, D.F. Buscher, N.M. Elias, C.A. Hummel, and D. Mozurkewich. I thank the Alexander von Humboldt foundation for support through a Feodor Lynen fellowship.

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