THE CALIBRATION OF INTERFEROMETRICALLY DETERMINED PROPERTIES OF BINARY STARS

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ABSTRACT. With the advent of speckle interferometry, high angular resolution has begun to play a routine role in the study of binary stars. Speckle and other interferometric techniques not only bring enhanced resolution to this classic and fundamental field but provide an equally important gain in observational accuracy. These methods also offer the potential for performing accurate differential photometry for binary stars of very small angular separation. This paper reviews the achievements of modern interferometric techniques in measuring stellar masses and luminosities and discusses the special calibration problems encountered in binary star interferometry. The future possibilities for very high angular resolution studies of close binaries are also described.

1. INTRODUCTION

Interferometry has been applied intermittently to the examination and measurement of close visual binaries (where the word "visual" is used here in the context of direct resolution by any means) since Anderson and Merrill used Michelson interferometry at Mt. Wilson during 1919-21 primarily for resolving Capella (Merrill 1922). It was not until speckle interferometry was first proposed by A. Labeyrie (1970) and subsequently demonstrated by Labeyrie and his collaborators (Gezari et al. 1972) that an interferometric technique of exceptional accuracy was routinely applied to a wide sample of binary stars. Visual interferometry, particularly as developed and pursued by W. S. Finsen at Johannesburg (Finsen 1971), provided a gain in resolution while maintaining the same level of accuracy as micrometry. A photoelectric version of Michelson interferometry provided promising initial results (Wickes and Dicke 1973), but no sustained effort using that approach followed upon the initial success. For a complete listing of modern interferometric approaches to binary star astrometry, the reader is directed to the catalog of McAlister and Hartkopf (1984), hereafter referred to as MH.

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Speckle interferometry employing photon detecting cameras at 4-meter class telescopes is capable of resolving 15th magnitude binaries with separations down to $0\overset{''}{.}025$. Most of the speckle results have so far been for objects brighter than 8th magnitude, and there is much useful work to be done in this regime, but it is likely that further speckle programs will push resolution toward a significantly fainter limit and give greater emphasis on employing analysis procedures capable of extracting differential photometric information from speckle pictures. The potential in this latter area has already been demonstrated, and a great deal of very useful information is likely to follow in the coming few years as close visual pairs are resolved photometrically as well as spatially.

Relatively few in number but important results have come from long baseline optical interferometry to date. As has been pointed out many times, the principal reason for the short supply of accurately known stellar masses and luminosities is not due to any paucity of binary stars. It is instead the result of the inability of any one technique to determine all the necesary parameters and the shortage of systems amenable to study by more than one technique. Where speckle interferometry using single telescopes has increased the overlap between visual and spectroscopic binaries, long baseline interferometry will subject virtually every spectroscopic binary to direct resolution.

Interferometric measurements of binary stars can be expected to make substantial contributions to the calibration of stellar masses and luminosities. When long baseline instruments are fully functional, we can look forward to direct measurements of the diameters of the individual components of binaries and hence to major contributions in calibrating emergent fluxes and effective temperatures of stars of known mass. Obtaining such complete and fundamentally important data for stars should serve as strong motivation to the few groups around the world who are working in the extremely challenging area of long baseline optical interferometry.

2. INTERFEROMETRICALLY DETERMINED MASSES AND LUMINOSITIES

The contributions to the empirical mass-luminosity relation made from combining interferometric and spectroscopic observations are shown in Figure 1 in which are also plotted the points considered to be reliable by Popper (1980). The values for α Virginis were determined with the intensity interferometer at Narrabri (Herbison-Evans et al 1971) which concurrently determined the angular diameter of α Vir A. The orbital solution of α Aurigae by Merrill (1922), which has been only slightly modified by extensive modern measurements (McAlister 1981), and its combination with spectroscopic data is discussed by Batten et al (1978). Speckle interferometry has been responsible for the remaining additions to the mass-luminosity relation in Figure 1 with specific references to the individual studies available from MH. Popper (1980) considered only the analyses of α Aur, α Vir and 12 Per

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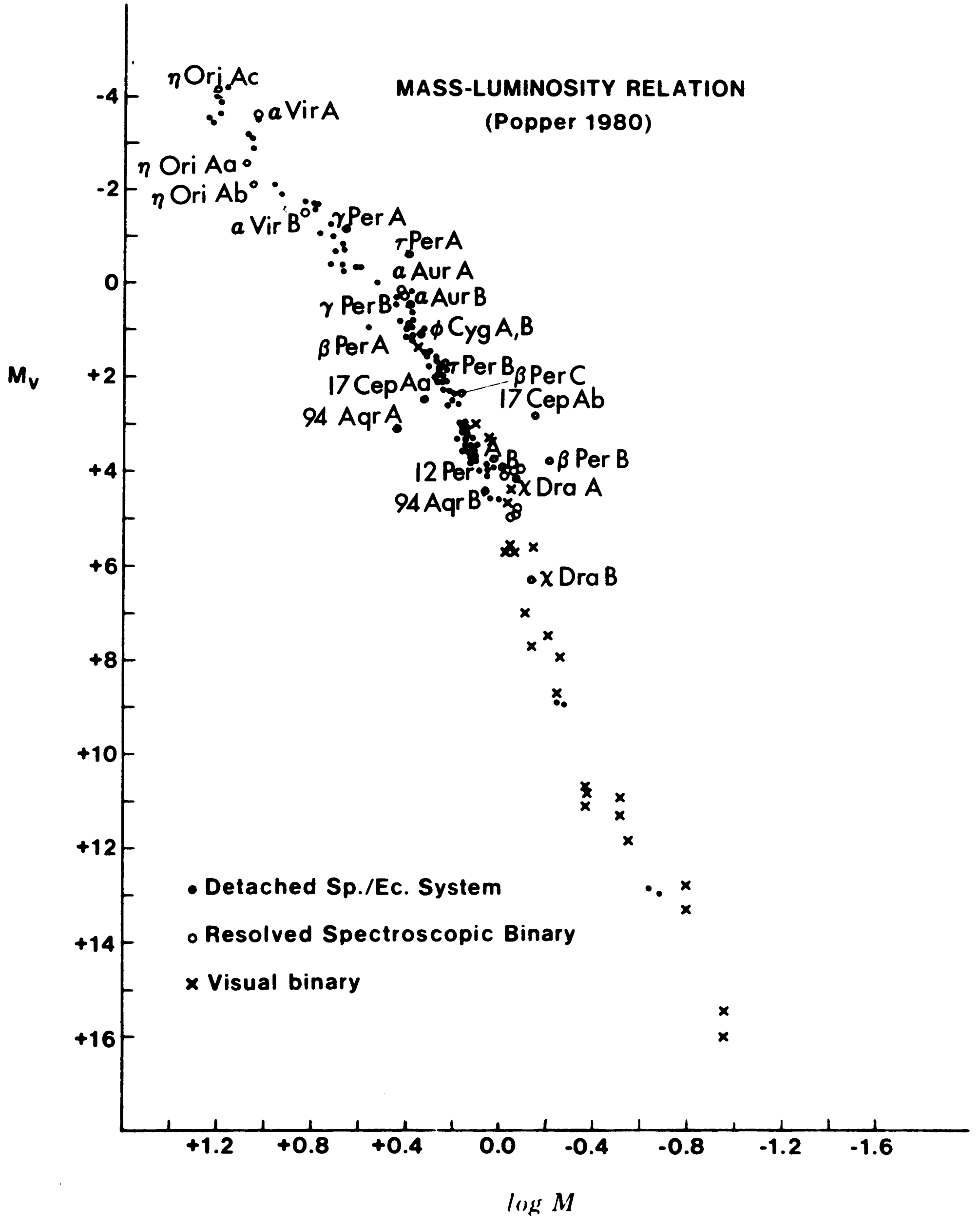

FIG. 1. Points added to the empirical mass-luminosity relation by interferometry are shown plotted against reliable other determinations as given by Popper (1980). Complete references to the individual analyses can be found in the catalog of McAlister and Hartkopf (1984).

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to be sufficiently free from significant future revisions to be considered reliable. Analyses too recent to be included in Popper's review for χ Dra and ϕ Cyg yielded formal errors in the masses of less than 10%. It is possible that the spectroscopic mass ratio for χ Dra may be revised (F. C. Fekel, private communication) thus affecting the conclusion that the components are excessively luminous for their masses. The mass ratio for ϕ Cyg should be less of a problem since the components are of similar luminosity and the velocities are relatively free of blending effects. In this case, however, the system always has a separation less than $0\overset{''}{.}04$ and is frequently unresolved. The residuals to the six existing speckle measurements of ϕCyg are no greater than $0\overset{''}{.}002$ and it seems unlikely that the orbital elements will change appreciably as further observations are accumulated.

Interferometric techniques capable of $0\overset{''}{.}025$ resolution are likely to continue to yield new masses and luminosities as spectroscopic binaries with long period orbits receive sufficient coverage of their relative visual orbits. Such systems often need modern spectroscopic observations, particularly to determine mass ratios, and small velocity amplitudes make this a challenging task. Of the 118 binaries newly resolved by interferometry which are listed in Table I (see MH for a complete list of references), 39 are spectroscopic systems of which 11 are double-lined. It is probable and certainly highly desirable that the fraction of spectroscopic binaries in this sample could be increased or that at least the mass ratios determined for systems exhibiting high eccentricity as they undergo periastron passage. Parallaxes forthcoming from the HIPPARCOS mission would then fill in the missing information for mass determinations.

As of early 1984, there were 3363 measurements of 824 systems derived from accurate interferometric observations with an additional 1863 negative examinations for duplicity (see MH). The mean measured separation is $0\overset{''}{.}32$ while the median is $0\overset{''}{.}21$. Thirty eight percent of the measurements are of separations no larger than $0\overset{''}{.}16$ and thus could not be generally provided by any other technique in standard usage. The remaining measurements have accuracies significantly improved over those obtained by other techniques for binary star astrometry. More than 90 percent of these data are from speckle interferometry with the majority being for systems in the northern hemisphere. Although the existing programs of binary star interferometry seem to be healthy and likely to continue, the field is by no means overcrowded. A program resident in the southern hemisphere would be especially welcome.

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TABLE I.

Binary Stars First Directly Resolved by Interferometry

Name		$\langle\rho\rangle$	MK Type	Name		$\langle\rho\rangle$	MK Type
HR 132	51 Psc	0."22	B9V	HR 5953	δ Sco	0.16	B0IV
HR 178	-	0.17	A7m	HR 5985	β Sco	0.11	B2IV-V
HR 233	-	0.05	B9V + G0III-IV	HD 144641	-	0.12	G5
HR 439	-	0.13	K0Ib + B9V	HR 6084	σ Sco	0.37	B8Vp
HR 483	-	0.55	G1.5V	HR 6148	β Her	0.09	G8III
HR 539	ζ Cet	0.06	K0III	HR 6168	σ Her	0.04	B9V
HD 12483	-	0.23	G5	HR 6237	-	0.05	F2V
HR 640	55 Cas	0.10	B9V + G0II-III	HD 155095	-	0.13	B8
HR 645	φ Per	0.04	G8III	HR 6388	-	0.04	K3III
HR 649	ξ¹ Cet	0.06	G6II-III	HR 6396	ζ Dra	0.05	B6III
HR 763	31 Ari	0.08	F7V	HR 6410	δ Her	0.10	A3IV
HR 788	12 Per	0.05	F9V	HR 6469	-	0.06	F9V
HR 793	μ Ari	0.05	A0V	HR 6485	ρ Her	0.29	B9III
HR 825	-	0.19	A5Ia	HR 6560	-	0.16	A5V + G5III
HR 838	41 Ari	0.30	B8V	HR 6588	ι Her	0.16	B3IV
HR 854	τ Per	0.05	G4III + A4V	HD 163640	-	0.09	A2
HR 915	γ Per	0.22	G8III + A2V	HR 6697	-	0.10	G2V
HR 936	β Per	0.07	B8V	HR 6742	W Sgr	0.12	F8Ib
HR 1010	ζ² Ret	0.05	G2V	HR 6779	ο Her	0.06	B9V
HR 1084	ε Eri	0.05	K2V	HD 167570	17 Sgr	0.27	A3 + G5
HR 1129	-	0.06	G0III + A3V	HR 6927	χ Dra	0.06	F7V
HR 1252	36 Tau	0.04	G0III + A4V	HD 171347	-	0.16	A2
HR 1331	51 Tau	0.09	F0V	HR 7059	5 Aql	0.13	A2V
HR 1346	γ Tau	0.40	K0III	HD 178452	-	0.12	A2 + G5
HD 283571	RY Tau	0.04	-	HR 7262	ι Lyr	0.08	B6IV
HR 1411	θ¹ Tau	0.15	K0III	HR 7377	δ Aql	0.13	F3IV
HR 1497	τ Tau	0.17	B3V	HR 7417	β¹ Cyg	0.42	K0III + B9V
HR 1569	6 Ori	0.33	A3V	HD 184467	-	0.08	K0
HR 1708	α Aur	0.05	G5III + G0III	HR 7441	9 Cyg	0.04	A0 + F5
HR 1788	η Ori	0.05	B1V	HR 7478	φ Cyg	0.04	G8III + G8III
HR 1808	115 Tau	0.09	B5V	HR 7536	δ Sge	0.05	M2II + A0V
HR 1876	37 Ori	0.05	B0III	HD 187321	-	0.40	A + G0
HD 37614-5	-	0.14	A + G	HD 190429	-	0.12	Oe
HR 2001	-	0.16	A4V	HR 7735	31 Cyg	0.03	K2II + B3V
HR 2002	132 Tau	0.04	G8III	HR 7744	23 Vul	0.24	K3III
HR 2130	64 Ori	0.05	B8III	HR 7776	β Cap	0.06	K0II-III + B8V
HD 41600	-	0.10	B9	HD 196088	-	0.05	A0 + G
HR 2304	-	0.04	A2V	HR 7906	α Del	0.14	B9IV
HR 2425	53 Aur	0.06	B9	HR 7921	49 Cyg	0.24	G8IIb
HR 2605	40 Gem	0.08	B8III	HR 7922	-	0.11	B6III
HD 52822-3	-	0.16	F5 + A	HR 7963	λ Cyg	0.03	B6IV
HR 2846	63 Gem	0.04	F5V + F5V	HR 7990	μ Aqr	0.04	A3m
HR 2861	65 Gem	0.04	K2III + K5III	HR 8047	59 Cyg	0.21	B1e
HR 2886	68 Gem	0.18	A1V	HR 8059	12 Aqr	0.05	G4III
HR 3109	53 Cam	0.04	A2p	HR 8119	I Cep	0.05	B0II
HR 3485	δ Vel	0.62	A1V	HR 8164	-	0.10	M1Ib + B2V
HR 3880	19 Leo	0.13	A7V	HR 8238	β Cep	0.18	B1III
+20°2465	Gl 388	0.08	M4Ve	HR 8264	ξ Aqr	0.03	A7V
HR 4365	73 Leo	0.04	K3III	HR 8417	ξ Cep	0.05	A3m
HR4544	-	0.17	K0III	HR 8485	-	0.52	K3III
HR 4689	η Vir	0.12	A2IV	HR 8558	ζ¹ Aqr	0.06	F6IV
HR 4785	β CVn	0.11	G0V	HR 8572	5 Lac	0.11	K7Ib + A8V
HR 4905	ε UMa	0.05	A0p	HR 8650	η Peg	0.04	GII-III + F
HR 4963	θ Vir	0.49	A1IV + Am	HD 215318	-	0.15	F8 + A5
HD 126269	-	0.05	F5 + A0	HR 8704	74 Aqr	0.07	B9III
HR 5435	γ Boo	0.07	A7III	HR 8762	ο And	0.33	B5III + A2p
HR 5472	-	0.04	F3V	HR 8866	94 Aqr	0.13	G5IV
HD 136406	-	0.36	K0	HR 9003	ψ And	0.28	G5Ib + A0V
HR 5747	β CrB	0.05	A8III	HR 9064	ψ Peg	0.19	M3III

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3. THE ACCURACY OF INTERFEROMETRY

The effects of systematic errors in angular separation measurements on mass and distance determinations for spectroscopic binaries resolved by interferometry depend upon the specific manner in which the data from the two complementary techinques are combined. The propagation of a relative scale error into the errors for the masses with a factor of three increase from Kepler's Third Law does not usually occur since the interferometry is most often used to solve for the inclination factor in the spectroscopically determined values for $M\sin^3 i$. The error in the distance determination would be linearly related to a scale error, and thus the luminosities would have relative errors sensitive to scale errors by a factor of two.

Interferometric measurements are of potentially very high accuracy and hence deserve high weight in the solution of a binary star orbit. With the current sample of several thousand measurements, it is possible to judge the level of accuracy of the data within and among the various groups of observers employing interferometric techniques. An earlier discussion of this topic (McAlister 1978) concluded that there is little evidence for significant systematic errors in speckle observations when compared to orbits of high quality. This has also been indicated more recently by Worley (1983) who found average residuals for 170 speckle observations from orbits of high quality of

$$\langle \rho\Delta\theta \rangle = +\ 0''\!.001 \pm 0''\!.007$$

$$\langle \Delta\rho \rangle = -0''\!.009 \pm 0''\!.015$$

It is interesting to note that the dispersion is twice as large in the separations as it is in the position angles. In both cases the dispersions are significantly larger than the mean differences. As will be seen later, this unfortunately does not imply that such orbits should be used for calibration purposes. Furthermore, comparison of speckle and micrometer measurements obtained nearly simultaneously shows no significant systematic difference at the limit of accuracy set by the micrometry. For 31 pairs of observations in the sense (visual-speckle) Worley (1983) found

$$\langle \Delta\theta \rangle = +\ 0^\circ\!.34 \pm 3^\circ\!.06$$
$$\langle \Delta\rho \rangle = -\ 0''\!.021 \pm 0''\!.042$$
for $$\langle \rho \rangle = 0''\!.38 \pm 0''\!.19$$

The dispersion in the diffences represents about 11 percent of the average separation and is probably inherent in the micrometer measures of such close pairs. Speckle interferometry should be routinely capable of measuring such separations to better than 1 percent accuracy, as speckle results are essentially derived from measuring the separation of two Airy disks having diameters on the order of $0''\!.03$. A level of 1 percent accuracy for binaries with separations of $0''\!.4$ essentially requires the centroiding on an Airy disk to an accuracy of

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about 10 percent. There is really little excuse for doing much poorer than this.

To assess the internal accuracy of interferometric measurements it is most profitable to examine the results for systems which have been extensively observed by various groups. Unfortunately such systems are rare. One binary star which has received a great deal of attention by interferometrists is β Cephei for which 42 measurements have been made between 1971 and 1981 by five different groups using at least six different telescopes. During that time span, β Cep closed in separation from about $0\overset{''}{.}25$ to $0\overset{''}{.}17$ while remaining nearly fixed in position angle. Figure 2 is a representation of these measurements in Cartesian coordinates. The solid line in Figure 2 is a linear fit to the GSU/KPNO 4-meter observations (filled circles) while the dashed line is an extrapolation ignoring elliptical motion back to the early French speckle results. In this straightforward attempt to compensate for orbital motion, the 18 GSU/KPNO 4-meter measurements show dispersions in angular separation of $\pm 0\overset{''}{.}0026$ and in position angle of $\pm 0\overset{\circ}{.}55$. The 7 GSU/KPNO 2.1-meter measurements show a degradation in accuracy with dispersions of $\pm 0\overset{''}{.}0094$ and $\pm 2\overset{\circ}{.}2$. While the 4-meter speckle observations approach a 1 percent level of accuracy, the 2.1-meter results emphasize the advantage of using the largest possible telescopes for speckle interferometry, not just to achieve the highest resolution but also to obtain the greatest accuracy.

The system comprising the star θ Virginis has been extensively observed in the course of the GSU speckle program but very little by other observers. A linear fit to 19 GSU/KPNO 4-meter measurements shows dispersions of $\pm 0\overset{''}{.}0048$ and $\pm 0\overset{\circ}{.}53$ and are again at the 1 percent level for this system which has an average separation of $0\overset{''}{.}495$.

It is seen that speckle interferometry can (and indeed should) achieve an internal accuracy of 1 percent. Although a perusal of the data in MH shows scattered indications of systematic differences among the observers, there does not yet exist sufficient overlap in the data to bring all interferometric results on a "system" that appears to be free of systematic error. The effects of these errors on the calibration of stellar masses and luminosities are certainly no worse (and perhaps considerably better if the consumer scrutinizes the data carefully) than the complementary spectroscopic, micrometer and astrometric material that joins with the interferometric results to yield fundamental astrophysical parameters.

4. CALIBRATION OF SPECKLE INTERFEROMETRIC OBSERVATIONS

4.1 Background

This section will concentrate primarily on observations of binary stars by speckle interferometry although discussions of standard stars and standard orbits pertain to any high angular resolution technique.

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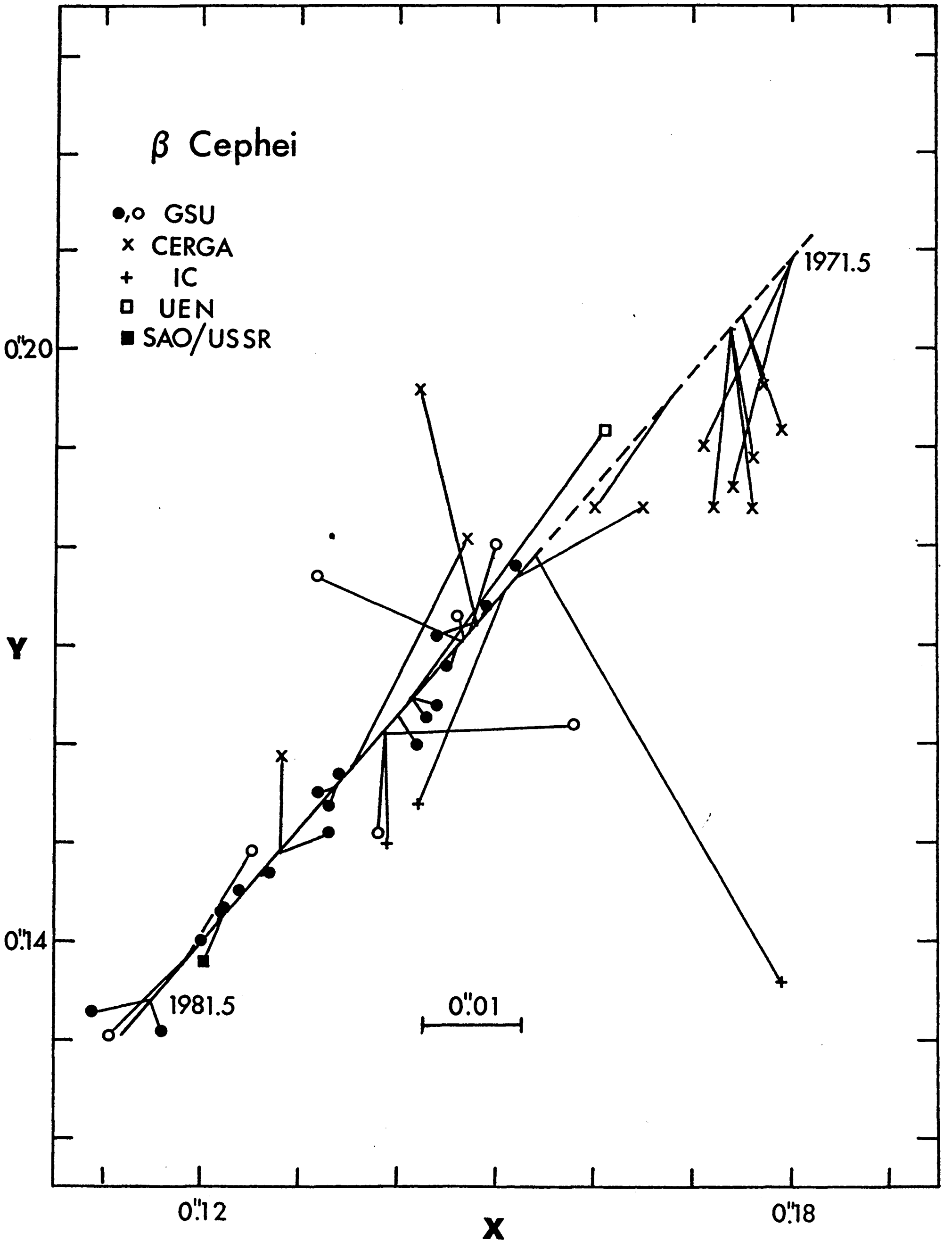

FIG. 2. Speckle interferometric measurements of the binary star β Cep are shown for the interval 1971-82 during which time the separation closed from 0".26 to 0".17 with little change in position angle.

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Because of its straightforward applicability speckle interferometry is more likely to be widely applied to high angular resolution measurements than other techniques, particularly long baseline optical interferometry, and there is a significant body of data from speckle work which can be used as a solid basis for this discussion. Reviews of speckle interferometry are given by Bates (1982), Dainty (1975), Worden (1977), Labeyrie (1978) and McAlister (1983).

Speckle pictures (or interferograms as some prefer to call them) are obtained during short time exposures which freeze the instantaneous effects of atmospheric turbulence. Speckle interferometry is essentially an examination of the spatial frequencies present in a speckle picture with the frequency cutoff determined by the aperture of the telescope. This permits the method to make diffraction limited measurements of spatial structure. If in one dimension O(x) is the instantaneous object intensity, then the instantaneous image intensity will be given by

$$I(x') = \int O(x)P(x'-x)dx$$

where P(x') is the instantaneous point spread function induced by atmospheric and telescopic effects. Taking the Fourier transform of this equation utilizes the convolution theorem to deconvolve the atmospheric and instrumental effects to obtain

$$i(u) = o(u)T(u)$$

where i(u) and o(u) are Fourier transforms of the image and object intensities and T(u) is the instantaneous transfer function and is the Fourier transform of the point spread function. The squared modulus of T(u) is the modulation transfer function (MTF) and it is the average value of the MTF which is normally utilized in speckle interferometry where the power spectrum

$$W(u) = \langle |i(u)|^2 \rangle = |o(u)|^2 \langle |T(u)|^2 \rangle$$

is calculated or determined in an analog fashion from a series of speckle pictures of an object.

An alternate and entirely equivalent processing procedure operating in the spatial rather than spatial frequency domain utilizes the average autocorrelation of the instantaneous image intensities

$$C(x) = \langle \int I(x') \, I(x'-x)dx' \rangle \, .$$

Dainty (1974) describes the effects of the transfer function on C(x) and shows that atmospheric seeing completely dominates over telescope aberrations under typical conditions. Figure 3 summarizes the analysis approaches of speckle interferometry to the special problem of binary star astrometry and Figure 4 shows a single speckle picture of α Aur with a composite autocorrelation of many such

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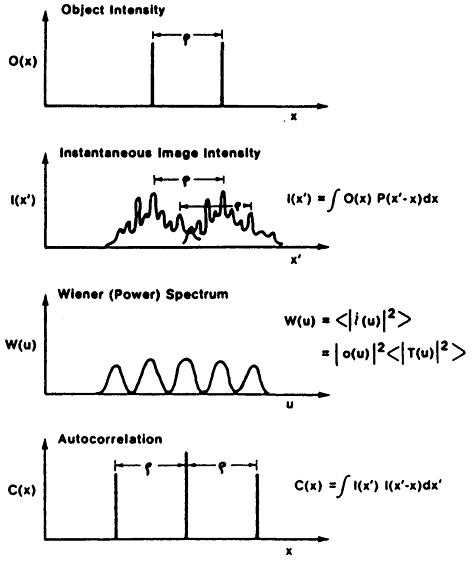

FIG. 3. A summary of the origin of speckle patterns and the analysis of speckle data for binary stars using either power spectrum or autocorrelation analysis is shown.

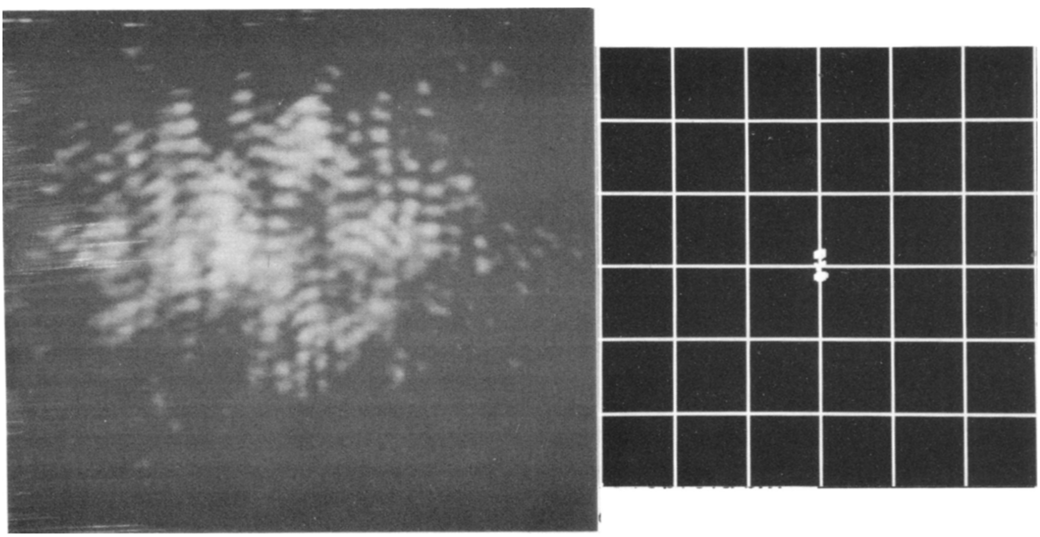

FIG. 4. A speckle picture of α Aur obtained with the GSU ICCD speckle camera at the KPNO 4-meter telescope in January 1984 is shown on the left where the picture is approximately 1" across. Individual pairs of speckles clearly show the 0".05 binary nature of the star oriented in the north-south direction. The picture on the right is the output from the hardwired digital vector-autocorrelator in use at GSU to reduce speckle data.

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pictures produced by a hardwired vector autocorrelator at GSU.

4.2 Atmospheric Effects

The atmosphere limits the applicability and accuracy of binary star speckle interferometry by the effect of non-isoplanicity and by introducing a major seeing component into W(u) or C(x). The limits of isoplanicity are under normal circumstances sufficient to permit separation measurements of up to several arcseconds - well into the realm of standard micrometer and photographic techniques - although the detailed influence of the transition from isoplanicity to non-isoplancity (which is equivalent to considering the transition from very high correlation to very low correlation between the speckle images of the components of a binary) has by no means been thoroughly studied. It is expected that loss of complete isoplanicity decreases the precision with which separations can be measured and may introduce systematic errors into differential photometry, but these effects enter at separations larger than those normally measured by speckle interferometry.

Atmospheric seeing effects are definitely of concern, however, and must be considered in the measurement of binary star separations, stellar angular diameters and differential photometric properties. Figure 5 is a representation of the analysis of a sequence of digital speckle pictures of the binary star ADS 4241 taken with the GSU ICCD speckle camera (McAlister et al 1982) at the KPNO 4-meter telescope in January 1984. ADS 4241 has an approximate angular separation at that epoch of 0".25. In Figure 5, the practiced eye can perhaps pick out the double speckled structure in the picture which is about 1".5 x 1".3 in size. Figure 5(b) is an integrated vector autocorrelogram of about 10 seconds of a stream of pictures of ADS 4241 recorded at 30 pictures per second. Contours show the overall structure of the seeing component which dominates the autocorrelogram as well as the two spikes indicative of the double star geometry at position angles of about 150° and 330°. A first approach at compensating for the seeing component is shown in Figure 5(c) which is the result of rotating the autocorrelogram 90° in position angle and subtracting it from the unrotated original version. This procedure would adequately subtract out the seeing component if the autocorrelogram were perfectly axially symmetric about the zero spatial component. Unfortunately, this is essentially never the case due to telescope aberrations, atmospheric dispersion, detector effects, etc., but this "rotation" algorithm is useful in locating the binary star spikes which are often small effects on the overall seeing slope. The radial profiles in Figure 5 (d) represent cuts through the autocorrelogram of 5(b) where the central profile passes through an estimate of the coordinates of the double star spike and the upper and lower profiles are cut in counterclockwise and clockwise directions at 30° intervals from the spike. The central profile clearly shows the asymetry of the spike resting on the sloping background of the seeing component. In order to compensate for seeing, third order polynomial fits to the top and

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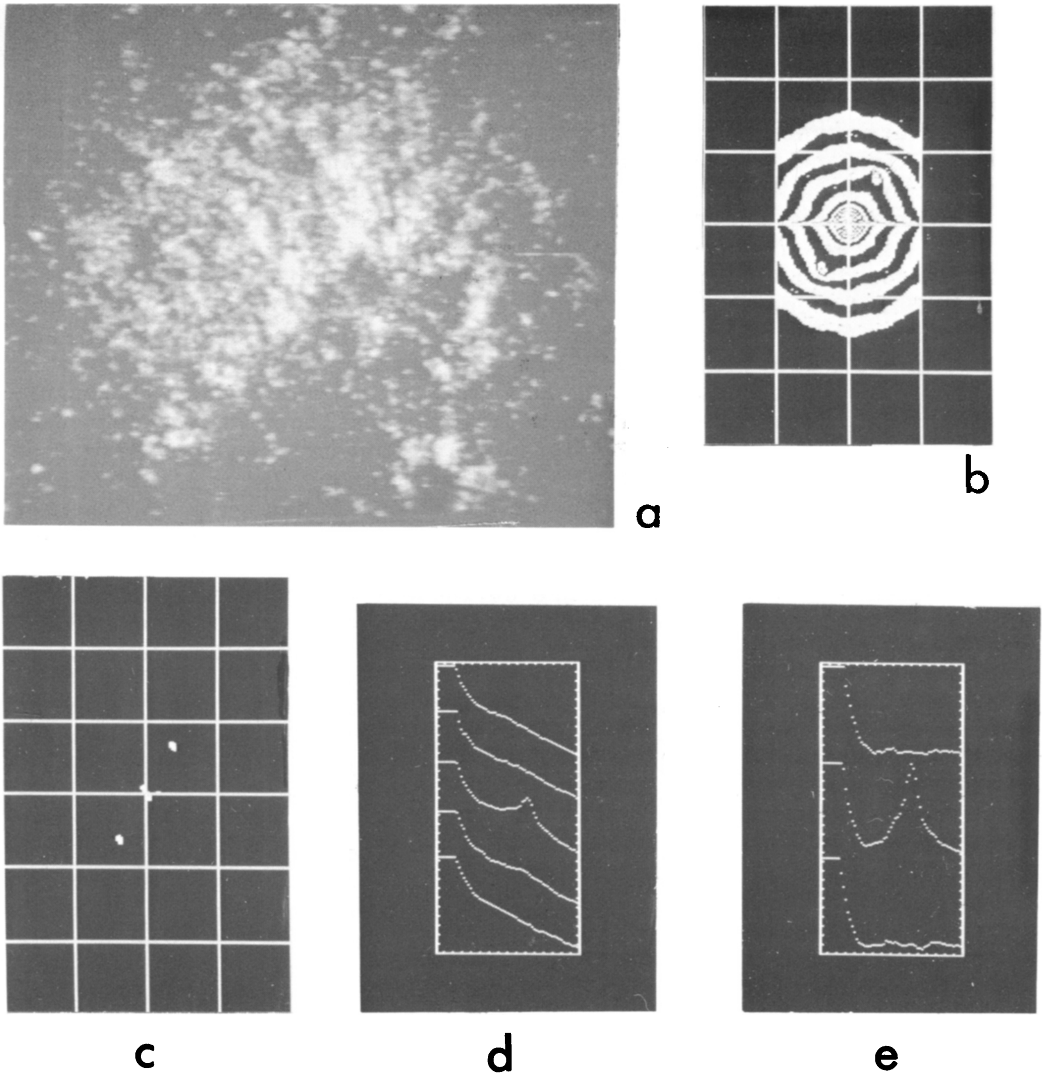

FIG. 5. A single speckle picture is shown in (a) of the 0".25 binary ADS 4241 taken with the GSU speckle camera at the KPNO 4-meter telescope in January 1984. The integrated autocorrelogram is shown in (b) and indicates the broad seeing induced component. The result of approximately correcting for seeing by rotating the autocorrelogram by 90° and subtracting it from the original is shown in (c). Radial profiles through the double star spike in the autocorrelogram and through the adjacent regions are shown in (d) and (e) before and after a more precise seeing correction.

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bottom profiles over a radial range encompassing the radial location of the spike in 5(d) were used to subtract out the sloping background by interpolating the coefficients of the polynomials to every point in the autocorrelogram between the two outer radial cuts. Figure 5(e) shows the resulting seeing corrected profiles which have been rescaled in intensity. In this case, the r.m.s. fluctuations in the background are at a level of 50 units in the relative intensity scale while the intensity of the binary star spike is approximately 2800 units. Centroiding the tops of the spikes in 5(d) and 5(e) shows a 5 percent increase in the separations deduced from the seeing corrected spike in comparison to the uncorrected spike with little effect on the position angle. This is precisely as would be expected and shows that failure to correct for atmospheric seeing effects in speckle interferometry can easily lead to systematic errors in separation measurements that could propagate to 15 percent errors in mass determinations.

One should ideally compensate for seeing effects by observing a nearby single star as close in time as possible to the program star observation. In practice this tends rarely to produce satisfactory compensation because of non-stationary seeing conditions and variations in the instrumental response and in the analysis of the separate data sets. This is more of a problem where the goal is to measure angular diameters or extended structures where the precise shape of the seeing corrected autocorrelogram is needed than in the case of binary star measurement where the background is only to be flattened. Seeing similarly affects measurements of fringe spacings made from power spectra. The systematic effect on the final separation measurement is, however, significantly reduced because the fringe spacing is a differential measure from a set of fringes which all tend to be shifted toward the central fringe by similar amounts, at least to first order. (McAlister 1978).

4.3 Angular Scale Determination

In transforming the linear measurement from an autocorrelogram or power spectrum of speckle data to an angular separation on the sky with an accuracy of 1 percent or better is somewhat of a challenge. Few large telescopes have had their focal lengths determined with this accuracy and so a laboratory measurement of the magnification of a speckle camera system is usually insufficient.

A very effective way of measuring the scale in the focal plane of the speckle camera is to turn the telescope into a Michelson interferometer by placing a double slit mask over the entrance aperture. This may be cumbersome for telescopes of large aperture, and it is possible to select an intermediate pupil at which such a mask can be placed. The projection effects of extrapolating this mask onto the entrance pupil require a knowledge of the focal length of the telescope and the location of the mask in the beam. This procedure was followed for the 4-meter telescope on Kitt Peak (McAlister 1977) and allowed a scale and orientation calibration with limiting accuracies of ±0.6

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percent in angular separation and ±0°2 in position angle. The double slit calibration mask has been used during more than 25 observing runs on that telescope with two speckle camera systems and has permitted us to establish what we believe to be a very uniform geometric calibration for our series of binary star speckle measures.

4.4 Calibration Standard Stars

A purely internal scale calibration procedure is ideally desirable but is occasionally not practicable. This is particularly the case where itinerant instruments are used at remote telescopes on a visiting basis, a circumstance which is now almost standard practice. This brings up the question of standard stars or standard orbits. It seems a pity when one uses techniques with potential high accuracy of angular measure to flip through a catalog, pick out a convenient binary star and adopt its published separation as a scale calibration. This can result (and has!) in scale errors of 50 percent or worse.

Choosing binary star orbits, even those which can be judged as definitive on the basis of orbital coverage, as standards for scale determination can also be treacherous. Comparison of the "Fourth Catalog of Orbits of Visual Binary Stars" (Worley and Heintz 1983) with the catalog of interferometric measurements (MH) shows 21 systems having definitive orbits which have received modern attention from interferometry. Table II contains a summary of the residuals to seven of these orbits for which there are more than a handful of interferometric measurements. If we consider only the GSU/KPNO measurements, which probably have the most uniform internal calibration, then it is seen that three of the orbits in Table 2 (ADS 1598, 9617, 11060) yield average residuals insignificantly differing from their dispersions and within 2 percent of the average separations of the systems. The remaining four orbits (ADS 1123, 6650, 8804, 14073) show statistically significant systematic residuals ranging from -6.7 to +8.8 percent of the average separations observed. In every case there is no indication of any significant systematic problems with position angles. This result does not contradict the conclusion of Worley (1983) quoted in Section 3 since the average percentage residual in the separations for the orbits in Table II is only +0.8 percent. Although there is no overall systematic trend between interferometric measurements and orbital ephemerides, there are strong differences when one considers orbits on an individual basis. Unfortunately, the latter procedure is what one follows in selecting orbits for calibration purposes. To further complicate matters, it can be expected that the degree of agreement with a particular orbit may vary with mean anomaly.

One orbit which perhaps can be used for calibration purposes is that of α Aur as shown in Figure 6 (McAlister 1981). Residuals to that orbit for 56 observations using four different interferometric techniques by seven different observing teams are

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TABLE II. Average Residuals of Speckle Observations to Definitive Orbits

ADS	<Δρ> All (N) GSU (N)	<ρ> Δρ/ρ	<Δθ> All (N) GSU (N)
1123	+0ʺ.025±0ʺ.013(14) +0.026±0.009(9)	0ʺ.296 +8.8%	+0°.5±2°.1 -0.2±1.5
1598	-0.005±0.008(11) -0.003±0.004(10)	0.665 -0.5%	-0.5±1.3 -0.2±0.9
6650	-0.044±0.015(14) -0.046±0.007(8)	0.852 -5.4%	-0.9±1.6 -0.5±0.7
8804	+0.032±0.019(25) +0.033±0.006(19)	0.389 +8.5%	+1.0±1.6 +1.2±0.5
9617	-0.005±0.010(12) -0.008±0.006(10)	0.453 -1.8%	+1.0±1.5 +0.8±0.9
11060	+0.004±0.005(20) +0.003±0.003(16)	0.343 +0.9%	+0.1±0.8 +0.1±0.7
14073	-0.036±0.012(27) -0ʺ.038±0ʺ.005(18)	0.569 -6.7%	-1.0±2.9 -0°.1±0°.9

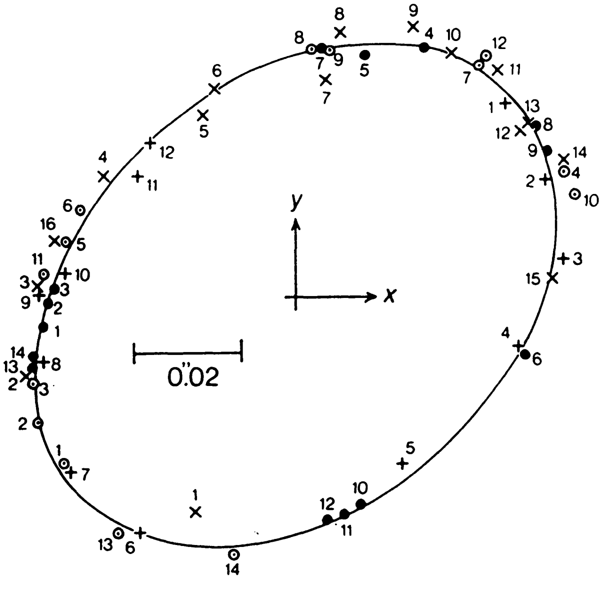

FIG. 6. Measurements from four interferometric techniques of the resolved spectroscopic binary α Aur are shown along with the apparent relative orbit (from McAlister 1981)

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$$\langle \Delta\theta \rangle = -\,0^\circ\!.06 \pm 2^\circ\!.14$$
$$\langle \Delta\rho \rangle = +\,0''\!.0001 \pm 0''\!.0021$$

and the internal error of the calculated semimajor axis is +0.0001. Further thought shows that even this orbit is not well suited to calibration since only the largest telescopes can resolve it in the first place and then measure it with an accuracy of $\pm 0''\!.002$ which is already about 4 percent of the average separation of $0''\!.055$. An accuracy of 1 percent is beyond reach if Capella is the only source of calibration. It must be concluded, therefore, that there are presently no binary star orbits which can be used unequivocally for calibrating angular scale to an accuracy of 1 percent.

As an alternative to standard orbits, it has been suggested (McAlister and Hartkopf 1983) that all interferometric observers adopt a set of standard stars for binary star interferometry. This list is reproduced here in Table III. Extensive observation of these objects will eventually lead to standard orbits in some cases. It will more generally define a set of slowly moving systems, such as θ Virginis, whose geometry can be frequently measured by (hopefully) several groups employing independent scale calibration. These objects, which are distributed all over the sky, can thus serve as tie-in stars to a system of accurate absolute angular calibration.

4.5 Photometric Calibration

Interferometric techniques offer the potential for performing photometry of the individual components of close visual binaries. This is extremely important since no other technique, except for the highly restricted method of lunar occulations, can obtain this information over the separation regime accessible to interferometry. Several approaches have been tried for speckle interferometry using actual data (Hege et al 1983, Cocke et al 1983, Bagnuolo 1983, Weigelt and Wirnitzer 1983, and Baguolo and McAlister 1983) and all rely upon the ability to perform accurate intensity calibration of speckle pictures. With the increasing use of solid state detectors in speckle cameras, such calibration is certainly feasible. Although "speckle photometry" is still in a developmental stage, there is every reason to believe that accurate photometry will be forthcoming for the components of binary systems once generally considered to be beyond the reach of photometric resolution.

5. POTENTIAL FROM VERY HIGH ANGULAR RESOLUTION INTERFEROMETRY

While interferometry using single telescope apertures has definitely enhanced the potential of binary star astrometry, the application of long baseline interferometry will quite literally revolutionize the field. Simple inspection of Kepler's Third Law shows that, for a given distance, an increase in limiting resolution from $0''\!.025$ as in the case of speckle interferometery at a 4-meter telescope

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TABLE III

Standard Stars for Binary Star Interferometry

HR	ADS/Name	SAO	α (1950)	δ (1950)	m	Δm	N_{obs}	t_f (1900+)	t_l (1900+)	<P.A.>		<Sep.>		comment
132	51 Psc	109262	$00^h29^m48^s.8$	+06°40'47"	5.7	0.7	6	77.7	81.5	95°.4	±0°.6	0".236	±0".005	no orbit
404	1123	129277	01 21 49.6	-07 10 30	5.9	0.2	14	75.6	80.9	217.2	0.8	0.346	0.009	P = 16.1 yr
719	Kui 8	110542	02 25 24.9	+01 44 16	6.5	0.4	12	76.9	81.7	32.5	0.2	0.510	0.001	no orbit
1199	Kui 15	111469	03 49 20.1	+06 23 10	5.7	0.1	8	76.9	80.9	208.4	0.2	0.645	0.003	no orbit
-	Stt 97	76954	05 02 36.5	+22 59 38	6.7	1.5	8	76.9	80.9	153.4	0.3	0.362	0.001	no orbit
1946	4265	94759	05 38 24.2	+16 30 35	4.9	0.4	10	76.9	80.9	237.9	0.2	0.347	0.001	P = 95.4 yr
2678	5795 AB	152394	07 04 19.8	-11 12 57	5.4	1.3	4	76.9	80.9	116.5	0.2	0.557	0.002	no orbit
2982	6313 AB,C	115839	07 40 31.4	+00 18 33	6.2	1.8	5	76.3	80.2	228.5	0.4	0.818	0.008	no orbit
3269	Fin 346	116630	08 17 12.2	+04 06 23	6.1	0.0	9	76.9	80.9	74.9	0.4	0.274	0.003	no orbit
3744	7382 AB	136861	09 24 47.6	-09 00 21	6.5	0.0	4	76.9	80.2	196.2	0.5	0.349	0.001	no orbit
4347	8086	156528	11 10 01.4	-18 13 39	6.1	0.4	10	76.0	81.4	333.3	0.4	0.250	0.004	P = 233 yr
4789	Wrh	82390	12 32 21.6	+22 54 15	4.8	2.4	10	76.3	81.5	12.4	0.3	0.356	0.001	no orbit
4963	θ Vir Aa	139189	13 07 21.5	-05 16 21	4.4	1.5	27	76.0	81.5	325.3	0.2	0.495	0.001	no orbit
-	9392	120673	14 46 24.2	+06 09 46	6.7	0.0	8	78.3	81.5	296.5	0.8	0.363	0.010	P = 228 yr
5654	Cou 189	101429	15 09 47.7	+19 09 47	5.9	1.9	8	78.1	81.5	145.5	0.1	0.461	0.003	no orbit
5850	9758	101699	15 40 50.3	+13 49 33	6.4	1.0	9	76.4	81.5	2.5	0.1	0.682	0.003	no orbit
-	9932	140981	16 05 42.9	-09 58 09	6.9	0.3	6	78.6	81.5	192.5	0.3	0.384	0.007	P = 55.0 yr
6627	10795	103106	17 44 55.5	+17 42 51	5.7	1.3	12	78.3	81.7	267.5	0.3	0.574	0.002	no orbit
6795	11111 AB	123187	18 07 04.6	+03 59 00	5.7	1.2	12	78.3	81.7	333.3	1.0	0.339	0.002	P = 270 yr
7285	12160 AB	104602	19 10 19.8	+16 45 40	6.7	1.3	4	76.6	81.7	137.9	0.1	0.681	0.001	no orbit
7497	12808 AB	105168	19 40 12.8	+11 42 27	5.3	1.2	8	76.5	81.7	76.3	0.1	0.456	0.001	no orbit
7882	14073 AB	106316	20 35 12.2	+14 25 12	3.6	1.0	24	75.6	81.7	182.5	1.5	0.538	0.008	P = 26.6 yr
-	14648 Aa	145118	21 04 45.8	-08 26 13	8.1	0.3	2	78.6	81.7	90.7	0.1	0.256	0.001	no orbit
8566	15988	127551	22 27 26.2	+04 10 38	5.5	1.4	10	76.6	81.7	117.1	0.1	0.818	0.005	P = 140 yr
8739	16428	108307	22 56 41.6	+11 27 40	5.8	1.3	8	78.6	81.7	297.3	0.5	0.600	0.002	P = 270 yr
8890	16708	165658	$23^h20^m02^s.0$	-15°18'50"	5.2	0.7	6	76.5	81.7	102°.0	±0°.2	0".412	±0".003	P = 63.2 yr

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to the $0\overset{''}{.}0002$ limit as an example for an interferometer with a 300-meter baseline results in a gain in sensitivity to shorter periods by a factor of $(0\overset{''}{.}025/0\overset{''}{.}0002)^{3/2} \cong 1400$. Where speckle interferometry now resolves systems having periods of years, a long baseline interferometer will resolve binaries having periods of hours! A two solar mass binary at a distance of 100 pc could be resolved as long as the period exceeded 18 hours corresponding to a semi-major axis of only 0.020 A.U. A system of the same total mass could be resolved from a distance of 1000 pc with a period as short as 23 days.

Observations of double-lined spectroscopic binaries offer the most promising returns from very-high angular resolution interferometry of binary stars. Distances determined for these objects are independent of the effects of interstellar extinction (and can in fact be used as a probe of the interstellar medium) and can potentially penetrate to distances well beyond the effective limit for trigonometric parallaxes while preserving the directness and uniqueness of a simple geometric technique. Single-lined spectroscopic binaries do not so easily yield a complete set of orbital and physical parameters since the linear scale of the relative orbit is not obtainable from the radial velocities of just one component. If the trigonometric parallax is known and the apparent orbit is determined interferometrically then the resulting mass sum can be combined with the spectroscopically determined mass function to give the individual masses. The HIPPARCOS astrometry satellite should eventually provide parallaxes of great value in this application.

By determining spectroscopic parallaxes for the objects included in the "Seventh Catalogue of the Orbital Elements of Spectroscopic Binary Systems" of Batten et al.(1978), Halbwachs (1981) calculated the expected angular separations at nodal passages. Of the 978 member systems in the catalogue, 683 binaries or 70% of the entire sample are predicted to have nodal separations exceeding $0\overset{''}{.}0002$ and would thus be good candidates for resolution by an interferometer having a baseline of 300 meters. Conservatively considering only double-lined systems as prime candidates due to their anticipated small magnitude differences and limiting the program to objects north of declination -20°, we find a sample of 180 double-lined spectroscopic binaries likely to be resolved by a 300 meter baseline interferometer. Of these, 102 systems are predicted to have separations greater than $0\overset{''}{.}0010$ and are almost certain to be resolved. Figure 7 presents a histogram of this last sample as a function of the MK spectral types available for the objects compared to the distribution currently available for the mass-luminosity relation. Important aspects of Figure 7 are the new large numbers of early type main sequence components as well as the substantial collection of evolved stars for which masses, luminosities and in many cases effective temperatures could become available.

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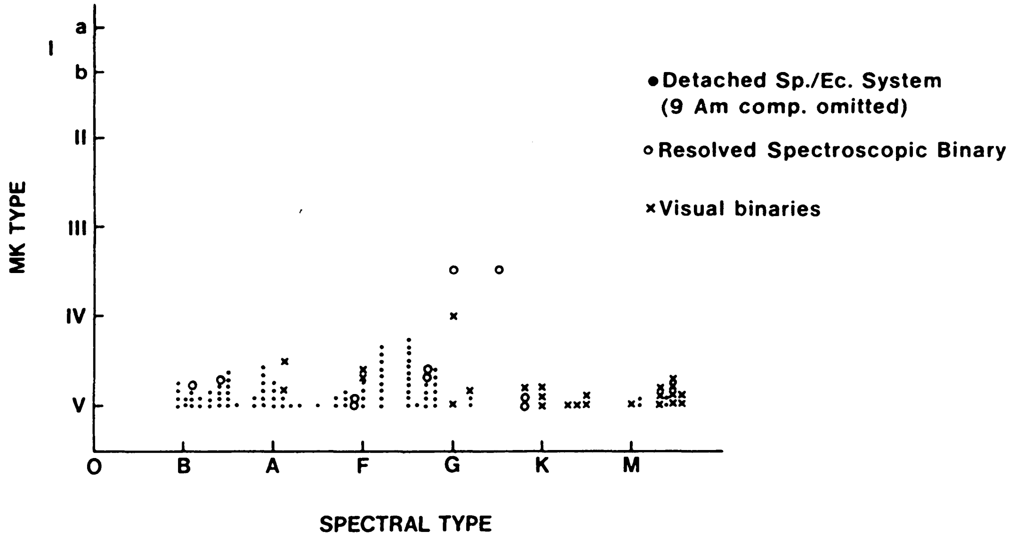

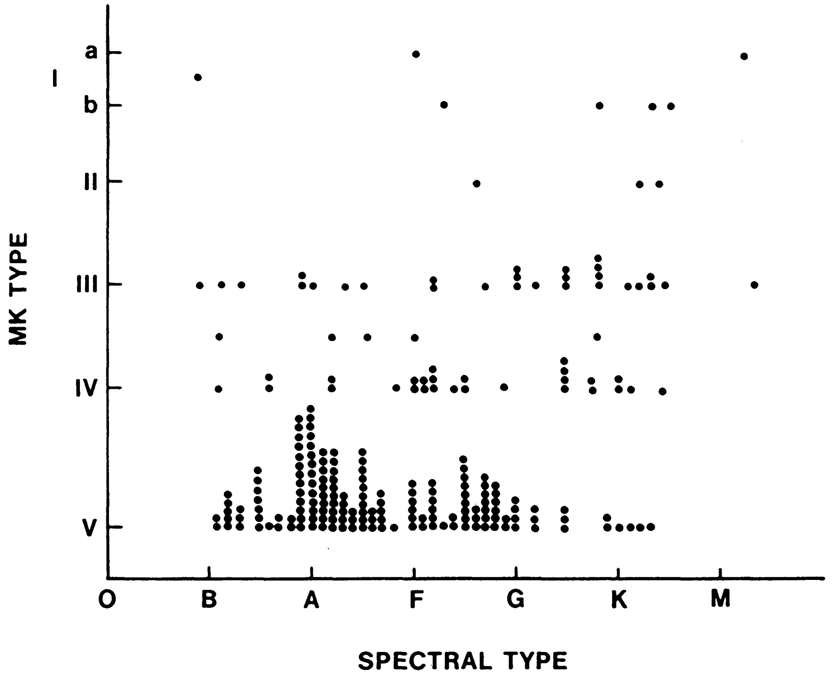

FIG. 7. The distribution of MK spectral types among the components of binaries considered by Popper (1980) as having reliably determined masses is shown in the upper histogram. The lower histogram shows the distribution of the components of double-lined spectroscopic binaries from the catalog of Batten et al (1978) which can be expected to have angular separations exceeding 0".0010 and thus be excellent candidates for long baseline optical interferometry.

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DISCUSSION

EVANS: Dr. Davis has emphasized the limitations of the occultation method and while, I agree with him, I feel I must emphasize what has been achieved so far. It has produced the major proportion of measured angular diameters. In some favorable cases, such as Alpha Tauri, where the repeatability of occulation observations has produced some twenty results; the mean value is uncertain by less than half a percent. The observed values range down, for later types, well below those values accessible to the speckle interferometrists. The observations do not require large telescopes, complicated equipment or large amounts of time so that even amateurs with relatively small telescopes can contribute. The possibility of multicolor observations on the same occasion is of value in the detection of possible variations with wavelength. As to errors: these are proportionally greater the smaller the star observed, but one needs to approach published values with reserve since methods of reduction vary quite widely. The quotation of the formal errors of a multiparameter fit usually give an unduly optimistic view of the situation. One should try a variety of trial diameters near the result of a multiparameter fit and assess critically the range over which diameter values might be acceptable. In certain cases there is no well defined best fit.

The occultation program has a future in the detection of close binaries, which in favorable cases are much closer than those accessible by speckle interferometry. Magnitude and color differences can be obtained from single observations and in some cases the ambiguity of quadrant of the speckle results can be removed. If numerous observations of the same system on the same or different occasions are available, conventional data for the separation and position angle can be derived and orbital elements improved or even derived. It is notable that the histogram of separations for A-type binaries differs from that given Dr. McAlister. For example, for the brighter A-type stars where observational selection is less severe, the numbers increase quite sharply for separations starting at the point where his begin to fall off.

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FRACASSINI: As regards the discovery of double stars by means of interferometry, I will ask something about the problem of Alpha Lyrae. In one of the first publications of the Narrabri researchers, Prof. Hanbury-Brown mentioned the problem of Alpha Lyrae, whose effective temperature, derived from angular diameter measures, is lower than that of Alpha Canis Majoris in spite of its earlier spectral type. In this connection Prof. Hanbury Brown mentioned the hypothesis by Petrie of the duplicity of Alpha Lyrae. That is not a trivial problem for the researchers of the Department of Physics at the University of Milan and their colleagues of Brera-Merate Observatory who have proposed Alpha Lyrae as a standard for the calibration of angular diameter determinations and, as I. N. Glushneva will say in her paper, this star is carefully studied by the researchers at the Sternberg State observatory in Moscow. Is there any news about this problem?

McALISTER: We have observed Alpha Lyrae on several occasions with our speckle camera and find no evidence of a companion. Our detectibility would be restricted to separations in excess of about 0.03 arcseconds and a magnitude difference less than about two magnitudes. Within these constraints, then Alpha Lyrae appears to be single to us.

BATTEN: High-dispersion observations of Alpha Lyrae at Victoria reveal no sign of variation in the radial velocity.

POPPER: I was disappointed that you did not discuss the application of your technique to the determination of color indices and magnitude differences (as described in your abstract) in binaries with good orbits. This information is often lacking so that fundamental properties of the components are not well known (but see K. D. Rakos, Astron. Astrophys. Suppl. 47, 221). At this time, this use of speckle observations could be of equal or greater importance than the astrometric results.

McALISTER: I did not say much about photometric determination from speckle interferometry because at the present time there are very few solid results available for demonstration. There are several very promising algorithms for extracting differential photometry from speckle data, as mentioned in my paper, and I believe that this potential may even be more important than the accurate astrometry speckle is providing. One member of our speckle group is devoting a major part of his time to implementing these algorithms and we aim, ultimately, at providing a catalogue of magnitude differences and color indices for binaries with separations of a few arcseconds down to about 0.03 arcseconds.

POPPER: Perhaps the most interesting result thus far from your work is for Chi Dra. The revised orbit, combined with published radial velocities, leads to a mass for the F7 V primary considerably less than one solar mass. No other late F star with well-determined properties has such a low mass. A critical observation is the radial velocity separation of the components. A very preliminary result by Tomkin and

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Fekel at McDonald Observatory shows that the spectral lines of the components are not clearly resolved except possibly at maximum separation. An underestimate of the separation by 1 or 2 km/s could remove much of the discrepancy in the mass of the primary, which has been interpreted as a consequence of a non-standard chemical composition. We await the results of further observations by Tomkin and Fekel.

McALISTER: I am glad to hear that a revised mass ratio for Chi Dra may be forthcoming. That, coupled with the more recent speckle results, will certainly warrant a re-analysis of this now puzzling system and may indeed show that it is not anomalous as it now appears.

STRAND: What is the limiting magnitude with the CCD system?

McALISTER: 15^{th} mag.

STRAND: I believe that you will be able to obtain measures of G 107-70, the close binary with white dwarf components, for which we now have a very precise orbit except for the value of the semi-major axis, which is of the order of 0.6" from 61-inch plates. With a parallax known to 1%, combined with a speckle interferometric measurement of separation, the system will give masses with a precision of a few percent.

McALISTER: We have not yet made a deliberate attempt to measure very faint binaries, but I do recall that we have very nice results on a 15^{th} magnitude system, which I believe is Ross 29. I do not remember if GL 107-70 is on our program, but I will certainly see that it is added if it is not already there.

GARRISON: I would like to second what was said by Dr. Popper about providing photometric information and to encourage you to extend your work to overlap with some the area-scanner work in the region of separations of 1 - 5 seconds of arc.

Chris Corbally at Toronto (now at the Vatican Observatory) finished a thesis last year in which he studied MK types for close visual binaries with separations of 1 - 5 seconds. The only photometric data available for comparison with his types are from the area scanner work of Hurly and of Rakos. Unfortunately there is little overlap between these two sources and they disagree with each other in those few stars. We can get good MK types for stars as close as 1" in good seeing, so this is important for studies of stellar evolution theories.

HEINTZ: The inclination usually is (along with the eccentricity) the element least reliably defined in astrometric (unresolved) orbits. I have a photographic series on Chi Draconis which I expect to complete shortly.

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