

Observations of binary stars by speckle interferometry – I

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Received 1977 November 14; in original form 1977 September 14

Summary. Speckle interferometry has been used to study a large number of binary-star systems and variable stars. Thirty-five observations on 30 objects are presented. These objects include six radial-velocity or photometric variable stars. Of these, new components are reported for the systems ϵ UMa, γ Boo and W Sgr and the system σ Sco is resolved into three components, confirming the results of Nather, Churms & Wild. The technique provides a very accurate means of measuring the separations of these systems.

Introduction

The technique of stellar speckle interferometry was suggested by Labeyrie [1] and even in poor seeing conditions, allows near diffraction-limited resolution of stellar diameters and binary or multiple-star systems. Reviews of speckle interferometry and its extensions have been made by Dainty [2], Labeyrie [3] and Worden [4].

The method is particularly suited to binary-star observations since measures of the separation and position angle of the stars may be readily derived. Previous observations using this method have been made by Gezari, Labeyrie & Stachnik [5], Labeyrie *et al.* [6], McAlister [7, 8, 9] and Blazit *et al.* [10].

This paper presents the results of 35 observations on 30 binary-star systems that have been performed using the 2.5-m Isaac Newton telescope of the Royal Greenwich Observatory, England, and the 1.9-m telescope of the South African Astronomical Observatory at Sutherland. The classical Rayleigh diffraction limits of these telescopes at a wavelength of 500 nm are 0.05 and 0.065 arcsec respectively.

The objects chosen for study included spectroscopic binary systems with long periods chosen principally from the 6th Catalogue of Batten [11], close visual-binary systems chosen from the 3rd Catalogue of Finsen & Worley [12] and variable stars. The visual-binary systems were observed because speckle interferometry was considered to be a more accurate means of determining separations than was previously available.

Techniques

The speckle interferometer has been described elsewhere [13] and was used in the standard form for all of the present measurements. All of the star images were recorded using an 8-ms exposure time and a filter bandwidth of 30 nm centred at 520 nm. The image scales were calibrated in two stages. First, the image scales at the Cassegrain foci of the telescopes were determined by photographing and measuring well known, widely separated double stars with a 35-mm camera back placed at the primary focal plane of the speckle interferometer. Secondly, the magnification of the complete interferometer from its primary focal plane to the 16-mm cine film was measured using a finely divided graticule as an object. From these measurements it was possible to calculate the image scale recorded on the 16-mm film in units of arcsec/mm. The orientation of the recorded images was determined in the following manner. The magnification of the interferometer was reduced so that the 16-mm film frame had an equivalent field of view of approximately 45×60 arcsec. A star was then trailed in either declination or right ascension across a single 16-mm frame fixing the orientation of that frame with respect to the direction of the celestial north pole. By comparing the power spectrum of this frame to the equivalent power spectra for binary-star systems the position angles of the systems could be calculated. By these means it is believed that the calibrations of scale and position angle are accurate to ± 1 per cent and $\pm \frac{1}{2}$ deg respectively.

As has been described previously [13] the average power spectra of the binary-star images were obtained by illuminating between 100 and 500 successive frames of the 16-mm cine film with coherent light from a laser and superimposing and recording the resulting power spectra on a single photographic plate. When this plate was developed an enlarged print was made on which the position angle and spacing of the fringes could be easily measured. The positions of the fringe maxima are significantly biased by the high gradients imposed by the envelope corresponding to the power spectrum of an unresolvable star. The positions of the minima are less affected due to the lower gradient of the envelope on which the minima lie. The measurements were therefore made on fringe minima. The envelope of the unresolvable star may be removed, for instance, by using a microdensitometer to digitize the power spectra; however, unless a large number of image elements can be used, the errors due to the quantization of the data may exceed those resulting from a direct measurement of the fringe minima.

Due to the symmetry of the image power spectrum there is an ambiguity of 180 deg in the measured position angle. For some observations which yielded good speckle contrast, it was possible to identify corresponding pairs of speckles and hence to determine the relative orientation of the brighter component.

Results

Table 1 lists the separations and position angles of 30 objects. A formal error can be assigned to each measurement of the separation by making a large number of measurements on a composite transform for each system. This has been done for a few systems and at this time it has been thought sufficient to give an indication of the quality of the fringes from which the measurement has been derived. Thus, in the column headed 'Quality' a class a, b, c or d is given. A measurement has been put into class 'a' if the fringe quality is such that the range of separations obtained in a series of determinations is no more than ± 2 per cent of the mean value. The corresponding figures for classes b, c and d are ± 4 , ± 10 and ± 20 per cent respectively. The formal error in position angle is typically 2 deg.

Table 1. Observations of binary-star systems.

Object	Epoch of Observation	Separation arc secs	Quality	Position			Epoch of Observation	Separation arc secs	Quality	Position		
				Angle Degrees	Residual arc secs	Degrees				Angle Degrees	Residual arc secs	Degrees
HD 6767 v Phe	1976.474	0.108	b	189.0	+0.062	-6.9	HD138690 γ Lup	0.563	a	282.5	-0.057	+4.4
ADS 1630 HD 12534 γ ² And	1975.953	0.527	b	109.0	-0.015	+0.2	ADS 9757 HD140436 γ CrB	0.236	b	132.0	-0.027	-2.9
ADS 4617 HD 40932 μ Ori	1975.953	0.374	c	17.7	+0.130	-0.8	HD143474 (Nor)	0.467	a	270.3	-0.067	+4.3
HD 76943 10 UMa	1975.956	0.412	c	73.3	-0.037	-8.7	ADS10009 HD147165 σ Sco	0.326	a	111.8	*	+
ADS 7158 HD 77327 K UMa	1975.950 1975.953	0.228 0.261	c a	290.2 288.7	-0.026 +0.007	+0.2 -1.3	ADS10374 HD155125 η Oph	0.290	a	276.9	-0.050(a) -0.031(b)	-0.5(a) +6.5(b)
ADS 7545 HD 85235 φ UMa	1975.956	0.245	b	77.8	+0.018(a) -0.026(b)	-12.6(a) -0.9(b)	ADS11029 HD164975 W Sgr	0.116	d	153.3	+	
ADS 7780 HD 90537 β L Mi	1975.953	0.527	b	222.7	-0.030	-4.1	ADS11468 HD171779 ADS11950	0.275	c	76.7	-0.049(a) -0.039(b)	-11.9(a) -7.4(b)
HD 98718 π Cen	1976.474	0.199	b	101.7	+0.123	+16.4	HD176687 ζ Sgr	0.484	a	245.3	-0.079	+1.2
ADS 8197 HD100203	1975.383 1975.953	0.450 0.412	b c	123.5 137.3	+0.033(a) -0.038(b) +0.014(a) +0.049(b)	-21.4(a) -8.2(b) -14.6(a) -0.2(b)	HD179366 ADS12973 HD187362 ζ Sge	0.468 0.156	a c	299.3 132.0	-0.141 -0.006	+10.6 -12.5
HD112185 ε UMa	1975.383	0.053	b	94.5	*	+	ADS14073 HD196524 β Del	0.569 0.565	a	336.5 348.5	-0.066(a) -0.049(b) -0.076(a) -0.061(b)	-14.8(a) -14.3(b) -4.2(a) -3.7(b)
ADS 9300 HD127762 γ Boo	1975.383	0.069	d	78.3	+		ADS14773 HD202275 δ Equ	0.117	d	209.7	-0.035	+7.0
ADS 9453 HD132219 59 Hya	1976.474	0.578	b	348	+0.229	-18.4	ADS15032 HD205021 β Cep	0.225 0.210	b a	37.2 47.3	*	+
ADS 9494 HD133640 44i Boo	1975.383	0.630	a	4.5	+0.020	-5.5	ADS16708 HD220278 97 Aqr	0.417	b	101.5	-0.043	+0.2
HD133955 λ Lup	1976.471	0.302	a	194.2	-0.077	+2.7	ADS16836 HD221673 72 Peg	0.504	b	252.8	+0.054(a) +0.088(b)	-9.4(a) -5.0(b)

* Radial velocity variable
+ Photometric variable

The sources of the orbital elements for which the residuals are derived are given in the notes. The means of the 27 residuals quoted here are: mean residual separation = -0.006 arcsec, mean position angle residual = -3.3 deg. This may imply a small systematic error in the position angles. The root mean squares of the separation and position angle residuals are 0.075 arcsec and 9.1 deg respectively.

Observations between epochs 1976.471 and 1976.477 were made using the 1.9-m telescope of the South African Astronomical Observatory, all others were made using the 2.5-m Isaac Newton telescope of the Royal Greenwich Observatory.

Notes

HD 6767 (ν PHE)

The observed separation is larger than that predicted by Finsen's [14] ephemeris. However, at the time of measurement the system was near to periastron.

ADS 1630; HD 12534 (γ^2 AND)

This is a quadruple system comprising star A which may be a physical companion and stars B and C which form a visual binary whilst star B is itself found to be a spectroscopic binary. Our observation of the visual system yields a separation close to that calculated from Muller's [15] elements. The total mass for the system B–C derived from Muller's dynamical parallax of 0.0107 arcsec is $5.67 M_{\odot}$. The spectroscopic parallax of γ And is 0.014 arcsec which gives a total mass of $2.53 M_{\odot}$. Maestre & Wright [16] have determined elements for the spectroscopic system B and suggest that the brighter component is of type B9 V yielding masses of 3 and $3.76 M_{\odot}$ which implies that the total mass of the system B–C must exceed that calculated by Muller. A slight reduction in the value of the dynamical parallax would avoid this difficulty.

ADS 4617; HD 40932 (μ ORI)

μ Ori is a triple system in which the stars A and B constitute a visual binary whilst star A is a spectroscopic binary with a period of 4.45 day. Orbital parameters were given by Bourgeois [17]. Alden [18] pointed out that the high eccentricity of the visual orbit leads to an unexpectedly high value for the mass of star B which is about 2.3 mag fainter than star A. The eccentricity was confirmed by Popper [19] who suggested that the mass discrepancy could be removed if star B had a large bolometric correction. Because the periastron passage occurred later than predicted, Popper revised Bourgeois' period of 17.5–18.5 yr. Finsen & Worley [12] suggested slight changes to the elements, but retained Bourgeois' period. Three observations of the visual system by speckle interferometry have been reported previously. Labeyrie *et al.* [6] report two observations and McAlister [9] a third. These observations and our own, which are listed in Table 2, have large residuals when compared to values calculated from the elements given by Alden [18]. No attempt has been made to modify all the orbital elements; however, using Alden's elements but taking a period of 20.2 yr with T occurring at 1929.8 yields an orbit which is a reasonable fit to all the separations. The root mean square of the residuals for the separations cited by Alden is 0.039 arcsec. If the speckle-interferometry results are included this becomes 0.057 arcsec. The rms of the residuals for all the separations using Alden's elements but taking $P = 20.2$ yr and $T = 1929.8$ is 0.037 arcsec. The deviation in the position-angle residuals on the other hand, is

Table 2. Speckle interferometry observations of μ Ori.

Observer	Epoch of observation	Separation (arcsec)	Position angle (degrees)	Residuals Alden's elements		Residuals $P = 20.2$ $T = 1929.8$	
				Separation (arcsec)	PA (deg)	Separation (arcsec)	PA (deg)
Labeyrie <i>et al.</i>	1972.96	0.290	158 (22?)	−0.063	+ 0.5	+ 0.006	−3.8
Labeyrie <i>et al.</i>	1973.20	0.274	157 (23?)	−0.073	+ 1.7	−0.024	−2.6
Morgan <i>et al.</i>	1975.953	0.374	17.7	+ 0.130	−0.8	−0.005	−6.1
McAlister	1975.960	0.376	19.3	+ 0.132	+ 0.8	−0.003	−4.5

somewhat greater with these values of P and T . A smaller deviation for these values of P and T may be produced by reducing the angle of the line of nodes; then the smallest deviation of the residuals for all the observations is 3.3 deg and occurs for a nodal angle of 25.5 deg. The best fit to the four speckle-interferometry results is obtained for a nodal position angle of 21.8 deg when the rms of the four position-angle residuals is only 1.3 deg.

HD 76943 (10 UMA)

This system has also been observed by McAlister [9] and his value for the separation is in good agreement with that calculated from Heintz's [20] elements. The observation reported here shows a larger residual.

ADS 7158; HD 77327 (κ UMA)

The first of these observations was made in very poor conditions and yielded a poor set of fringes. The second observation is in good agreement with that reported by McAlister [9] and shows only a small residual from Morel's [21] elements. In both cases the elements given by Baize [22] produce larger residuals than those of Morel.

ADS 7545; HD 85235 (ϕ UMA)

Orbital elements have been given by (a) Eggen [23] and (b) Heintz [24].

ADS 7780; HD 90537 (β LMI)

This system has been observed both visually and spectroscopically. The separations and positions angles measured by McAlister [9] and those reported here are in good agreement. They are slightly smaller than those derived from Baize's [25] elements.

HD 98718 (π CEN)

Although Newburg's [26] elements are derived from observations over more than a complete period there is a large residual in the separation. When observed the system was within a few months of periastron.

ADS 8197; HD 100203

The elements (a) given by Aitken [27] are based on observations of less than a period made before 1912. The elements (b) are given by Hable [28].

HD 112815 (ϵ UMa)

The Yale bright star catalogue cites this star as a spectroscopic variable with dual periodicity, $P = 4.15$ yr and $P' = 0.95$ day. The object is also a photometric variable with period 5.09 day. This observation detected duplicity with a separation of 0.053 arcsec, presumably resolving the longer period system. Merrill [29] using a Michelson stellar interferometer suspected the duplicity of ϵ UMa in 1922. The observed separation corresponds to the diffraction limit of the 2.5-m Isaac Newton telescope.

ADS 9300; HD 127762 (γ BOO)

This is a photometric variable star of tentative period 0.29 day which is also a member of a binary system with a separation of the order of 33.4 arcsec and a magnitude difference of 9.27. This observation apparently resolves the brighter primary into two stars separated by 0.069 arcsec.

ADS 9453; HD 132219 (59 HYA)

The observed separation is much larger than that derived from the elements given by Mourao [30] which give a period of 339.3 yr. Mourao's elements yield a total mass of $13.65 M_{\odot}$ which seems too large for a pair of A5 stars.

ADS 9494; HD 133640 (44i BOO)

This system has been studied extensively. The fainter component is a W Ursae Majoris variable and is a spectroscopic-binary system. The visual binary has been observed here. This value of the separation and that measured by McAlister [9] are slightly larger than the values derived from Heintz' [31] elements.

HD 133955 (λ LUP)

The observed separation is significantly different from the value derived from the elements which van den Bos [32] describes as 'preliminary'.

HD 137909 (β CRB)

Couteau [33] first resolved this spectroscopic system. Labeyrie *et al.* [6] and McAlister [9] have also observed it by speckle interferometry. The observations presented here are of poor quality, but the results are consistent with those of Labeyrie *et al.* and McAlister.

HD 138690 (γ LUP)

Heintz [34] reports that this orbit is not well known; his elements give somewhat larger separation and position angle than were observed.

ADS 9757; HD 140436 (γ CRB)

The separation is close to that observed by McAlister [9]. Both results are smaller than that derived from the orbit of Baize [35].

HD 143474 (ι NOR)

Visual observations of this system have extended over more than two periods. However, the separation reported here is significantly different from that derived from van den Bos' [36] elements.

ADS 10009; HD 147165 (σ SCO)

The measurement presented here cannot be that of the spectroscopic system observed by Struve, Sahade & Zeberg [37], but probably relates to the more distant companion observed by Nather, Churms & Wild [38] at a lunar occultation. The system is also a photometric variable.

ADS 10374; HD 155125 (η OPH)

The elements given by (a) Knipe [39] and (b) van Biesbroeck [40] are slightly different.

ADS 11029; HD 164975 (W SGR)

This is a Cepheid variable with a companion at a distance of 48 arcsec. This measurement resolves the variable star into two components.

ADS 11468; HD 171779

This appears to be part of a triple system. The elements given by (a) Wilson [41] and (b) Baize [42] are different, possibly due to the long period of the system. The observed separation is less than that derived from either ephemeris but it and the position angle are rather closer to Baize's values.

ADS 11950; HD 176687 (ξ SGR)

This system was carefully studied by van den Bos [43].

HD 179366

The observed separation is significantly less than that obtained from Heintz' [44] elements.

ADS 12973; HD 187362 (ξ SGE)

This is part of a triple system. Finsen's [45] observation covered two periods and yield a separation close to that reported here.

ADS 14073; HD 196524 (β DEL)

This system has been observed both visually and spectroscopically. The elements quoted by (a) Finsen [46] and (b) Couteau [47] each give a separation and position angle greater than those observed. The position-angle measurements were carefully checked in view of the large change between the two epochs. No errors in the measurements were detected.

ADS 14773; HD 202275 (δ EQU)

This system is a visual binary which has a rather short period (5.70 yr). The residuals are calculated from the elements of Luyten & Ebbighausen [48].

ADS 15032A; HD 205021 (β CEP)

ADS 15032A is the primary of the system β Cep. It is believed (Smith [49]) to be a binary system with a period of ~ 50 yr. There is also evidence of radial-velocity variations. This system was resolved by Labeyrie *et al.* [6] using speckle interferometry and later by McAlister [9]. Labeyrie noted anisotropic features in the power spectrum which might indicate other companions. Such features were not observed in the power spectrum derived from these observations.

ADS 16708; HD 220278 (97 AQR)

The residuals are derived from van den Bos' [50] elements.

ADS 16836; HD 221673 (72 PEG)

This system has a long period and the elements published by (a) Costa [51] (198.6 yr) and (b) Tel'nyuk-Adamchuk [52] (425 yr) differ. The observed separation and position angle are in reasonable agreement with the calculated values considering the uncertainty of the orbit.

Future work

The visibility of the fringes is dependent on the magnitude difference between the components of the binary system and can therefore be used to infer the relative masses of the two components. Unfortunately, this visibility also depends on the contrast of the recorded speckles so that it is affected by parameters such as the exposure time or filter bandwidth. The following technique has been developed for calibrating the fringe visibility in terms of magnitude difference. Artificial binary-star systems are generated from single stars by inserting doubly refracting calcite prisms into the light path of the interferometer. One or both of a pair of prisms is introduced to give apparent binary-star separations of approximately 0.08, 0.20, 0.28 and 0.48 arcsec for the Isaac Newton telescope. Assuming that the light from the star is unpolarized, these artificial binary stars are of equal magnitude. Magnitude differences of up to 5 or 6 can then be produced by adding a polarizing filter set at an appropriate angle to the optic axis of the calcite. The required angles are determined experimentally to allow for possible imperfections of the calcite or filter. The calibration procedure therefore consists of measuring the fringe visibility for a series of apparent magnitude differences under the same observing conditions as for the binary-star observations. Thus the magnitude difference of the binary-star system may be determined from the observed fringe visibility. However, the method does not make allowance for the effects of isoplanicity which lead to an apparent increase in the measured value of the magnitude difference for increasing separation of the binary stars. It is believed that this error is not serious for separations of less than about 0.5 arcsec [53].

This calibration procedure, which has been used in recent observations, was not in fact available when the early observations described here were carried out.

A further improvement in the observing technique will be obtained by the use of an optical system which will achromatize the speckle images. Under normal observing condi-

tions the speckle image exhibits two forms of chromatic dispersion: that introduced by the atmosphere at non-zero zenith angles can be corrected by a pair of prisms [13]. Measurements indicate that a radial dispersion of about 0.0027/mm is to be expected for the typical speckle images used in binary-star work. An optical system has been designed to produce an equal (variable) and opposite dispersion which will achromatize the speckle images. This will allow a much broader filter to be used (in some cases the filter may be omitted completely) when recording the images, and a gain of five to ten in the number of recorded photons may be achieved whilst maintaining the same speckle contrast. A disadvantage of the proposed optical design, which will be described in a future paper, is that it has zero field of view and therefore requires very accurate centring of the star image. The achromatic system will be mainly employed for close binary-star systems or single, resolvable objects.

Conclusions

The separations and position angles of 30 binary-star systems have been measured using speckle interferometry. The technique, which does not require good seeing conditions, yields very accurate values for the separations in observation times of only a few minutes per object. If large telescopes can be equipped with this relatively inexpensive instrument, double-star observers may expect considerable improvements in the accuracy of binary orbits, stellar parallaxes and stellar masses.

Acknowledgments

The authors would like to thank the referees of this paper for their extremely helpful comments. They also wish to thank the Science Research Council for financial support for the work and the directors and staffs of the Royal Greenwich Observatory, Herstmonceux, and the South African Astronomical Observatory for their valuable assistance.

RJS and DRB were in grateful receipt of a SRC Research Fellowship and Studentship respectively.

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