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Speckle interferometric measurements of binary stars. II.

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Summary. — We report speckle interferometric measurements of 87 binaries or suspected binaries observed with the 6 m SAO, 3.60 m CFH and ESO, and 1.93 m OHP telescopes. Four binaries are first resolved. Preliminary orbital parameters are proposed for two systems.

Key words : speckle interferometry — binary stars — stellar masses.

1. Introduction.

The astrophysical interest for the study of multiple systems by high angular resolution technics is now well established (McAlister, 1979a; Blaauw, 1981).

Observations of binary stars by speckle interferometry have been made by some groups managed by H. A. McAlister (USA), B. L. Morgan (UK), G. P. Weigelt (RFA). This paper reports the results of our observations of 87 multiple systems with the digital speckle interferometer developed by our group. These observations have been carried out as the continuation of our programs for stellar masses determination and the study of stars with composite spectrum (Labeyrie *et al.*, 1974; Blazit *et al*, 1977; Bonneau, 1979; Bonneau and Foy, 1980; Bonneau *et al.*, 1980; Ginestet *et al.*, 1980).

28 binaries were observed with the 6 m soviet telescope in September 1981.

The spectroscopic binary 6 Per and HR 8164, a spectrum binary, are resolved for the first time.

61 systems were observed at the Canada-France-Hawaii 3.6 m telescope in June 1980, March 1981, and March 1982. The astrometric binary Gl 388 is resolved for the first time.

4 couples were resolved with the 3.6 m telescope at the European Southern Observatory in June 1981.

Measurements of the visual binary i Ser and of the spectroscopic-interferometric binary β CrB have been obtained in June 1982 with the 1.93 m telescope of the Haute-Provence Observatory.

Send offprint requests to : D. Bonneau.

The small number of stars observed at ESO and OHP is due to poor weather conditions : cloudy night or very fast seeing.

We propose a preliminary relative orbit for η Vir and β CrB.

2. Observations and data reduction.

The observations reported in this paper were carried out with the digital speckle interferometer extensively described in Blazit *et al.* (1977) and Bonneau (1982).

At the 6 m and 3.6 m telescopes, it is attached to the prime focus whereas we work at the Cassegrain focus of the 1.93 m telescope.

The instrumentation includes :

— The optical interferometer which gives a high magnification of the stellar image, allows to select the wavelengths of observation (between λ 4000 Å and λ 8000 Å) and to compensate the atmospheric dispersion. We use spectral bandwidth $\Delta\lambda$ from 100 to 400 Å.

— The images are recorded in photon counting mode by a TV camera at the standard rate of 50 images/s. The integration time if usually 20 ms per frame. To remove the effect of the remanence and to reduce the integration time down to a few ms, we can use a mechanical shutter which is open during 20 ms or less, one frame over four. This mechanical shutter is in operation since March 1982.

— The digital autocorrelator is used for on-line data reduction but the images are recorded on video tape and re-analysed back to laboratory.

The data processing for the measurement of binary stars is extensively described in Bonneau and Foy (1980), Bonneau and Koechlin (1981) and Bonneau (1982).

The angular separation and the position angle are calculated from the position of the secondary peak in the average autocorrelation function of stellar images, using a calibration of the optical magnification and of the orientation of the instrumentation around the optical axis of the telescope.

Table I gives for each observing run the limit of angular resolution and the higher magnitude difference detected. These two parameters are function of the image quality. Also we give the angular calibration of the pixel in the autocorrelation which only depends on the optical magnification.

In the case of resolvable bright objects ($V \lesssim 10$), the detection of a companion essentially depends on the quality of the seeing. If the life time of the atmospheric turbulence is short in regard of the exposure time, the high spatial frequencies of the stellar images are lost, i.e. the central peak in the autocorrelation function of a point source is enlarged and the ratio of peak to pedestral intensities decreases. For a binary star, this effect results in a loss of angular resolution and a lower sensitivity to detect companion with high difference of magnitude.

3. Results.

Table II gives angular separations ρ and position angles θ for the resolved systems. There is an ambiguity of 180° in position angles which has been removed using published visual orbit when available.

Table III presents the comparison of our measurements with the computed positions for visual binaries with well known orbit. Orbital elements used for these estimates have been kindly communicated to us by P. Couteau.

Mean residuals for angular separations and position angles are $-0.002'' \pm 0.014''$ and $+0.4° \pm 1.6°$ respectively. This means that there is no systematic error in our measurements with respect to visual ones.

Table IV gives the residuals in angular separations and position angles for the spectroscopic binaries for which a relative orbit has been determined on the basis of speckle interferometric observations.

Table V lists the objects which have been found unresolved, taking into account the limitations imposed by conditions of observation (see Table I).

For the systems η Bir, β CrB, δ Sco and α DelAa, more than ten measurements are published since their first resolution making possible a preliminary analysis of the orbital motion.

We use the geometrical method based on the drawing of the ellipse for which the observed positions of the companion obey as well as possible the law of areas (Couteau, 1978). The geometrical analysis of this apparent orbit allows for a first determination of the orbital elements. These elements are then improved by a weighted least-square first order differential method in both position angles and separations (Simoes da Silva, 1966) using a routine kindly supplied by P. Morel.

In two cases, the iterative process does not converge. For α DelAa, the observed arc of trajectory is not long enough to allow for an unambiguous determination of the orbital period. For δ Sco, the observations are not uniformly set along the arc of trajectory so that the dynamical elements of the system are not well determined. However, for η Vir and β CrB, the process converges and gives a first set of orbital elements.

4. Notes for individual stars.

1. 6 per is directly resolved for the first time. This is a single line spectroscopic binary of period 4.5 y (No. 80 in Batten's catalogue), previously unresolved by speckle interferometry (McAlister, 1978b). It is interesting to note that Halbwachs (1981) predicted for this system a maximum angular separation of about 47 milliarcseconds. The determination of masses in this system will be important because the primary is classified K0 III (Popper, 1980).

2. μ Ari is an occultation binary (de Vegt, 1976) known to have a variable radial velocity (Abt and Biggs, 1972). This object first resolved with speckle interferometry by Blazit *et al.* (1977) shows a rapid orbital motion.

3. HR 3750. This single line spectroscopic binary ($P = 2.5$ y, No. 378 in Batten's catalogue) is also known as a close visual binary B 2530. Since 1976, the speckle interferometric observations by McAlister indicate that the system may have been closing. The primary is classified G2 V so that the companion should likely be a cooler dwarf; this seems to be confirmed from the magnitude differences we observed at λ 7500 Å, λ 5500 Å, and λ 4500 Å.

4. Gl 388 is a flare star (M 4.5 Ve) known as having an unseen companion with a period of about 27 y (Reuyl, 1943). This is the first direct resolution of the system. The companion has been detected only at λ 7800 Å. Observations of this system could be continued to precise the nature of the companion, which is expected to have a very low mass.

5. η Vir. The first resolved with speckle interferometry by McAlister (1978a) is not the double line spectroscopic binary (No. 499 in Batten's catalogue, $P = 72$ d) because the observed angular separations are much larger than the maximum value ($\cong 12$ m″) predicted by Halbwachs (1981) from the spectroscopic elements.

Between 1976 and 1982, the wide system exhibits a variation of about 180° in position angle. The analysis of the observations gives a preliminary determination for the elements of the relative orbit :

$$P = 13.0\ \mathrm{y}\,, \quad T = 1976.5\,, \quad e = 0.08\,, \quad a = 0.135''\,,$$
$$i = 49.4°\,, \quad \Omega = 172.5°\,, \quad \text{and} \quad \omega = 348.5°\,.$$

For the 21 published observations, the comparison between measurements and computed positions gives mean residuals of 0.2 ± 6.5 m″ in angular separation and $0.2 \pm 1.3°$ in position angle.

Adopting a distance of 70 pc derived from spectral classification and photometric data for the spectroscopic system (Conti, 1969), we found that the total mass of the triple system should be near 5 $m_{\odot}$. However the continuation of speckle interferometric observations is needed to improve the knowledge of this system and perhaps to detect the motion of the spectroscopic couple as a perturbation of the long period orbit.

6. β CrB (F0p) is a single line spectroscopic binary (No. 543 in Batten's catalogue) first directly resolved by speckle interferometry in 1973 (Labeyrie *et al.*, 1974). The geometric determination of the apparent orbit from the 27 published observations leads to the preliminary elements :

$$P = 10.48\text{ y}, \quad T = 1980.47, \quad e = 0.54, \quad a = 0.204'',$$
$$i = 110^{\circ}, \quad \Omega = 148^{\circ}, \quad \text{and} \quad \omega = 181^{\circ}.$$

Adopting the trigonometric distance of 30 pc, we found a total mass of about 2.1 $m_{\odot}$ for this system.

The mean residuals between observed and computed positions are $+ 0^{\circ} \pm 2.5^{\circ}$ in position angle and $+ 1$ m″ $\pm$ 11 m″ in angular separation. The elements P, e, ω agree with the values initially determined for the spectroscopic orbit by Neubauer (1944), but his time for the periastron passage, $T = 1980.18$, is not consistent with the value derived from speckle interferometric observations. Recent radial velocity measurements with CORAVEL (Mayor, 1983) suggest that the spectroscopic elements of Neubauer should be revised.

7. δ Sco. The companion of this star has been discovered by intensity interferometry (Hanbury Brown *et al.*, 1974) and first directly resolved with speckle interferometry by Labeyrie *et al.* (1974). The bright component of this system is a B0.5 IV star and the magnitude difference in the visible is about 2 (Hanbury Brown *et al.*, 1974; Labeyrie *et al.*, 1974).

The 18 published observations of this system seem to be compatible with an orbital period near 20 years. Elements of the orbit cannot yet be determined.

8. ζ Dra is a B6 III star first resolved by Starikova and Tokovinin (1981) who found for 1981.384 $\theta = 32 \pm 4^{\circ}$ and $\rho = 0.041 \pm 0.015$ with $\Delta m \sim 1$. This system could have a rapid orbital motion since its position angle has changed by about 23° and its angular separation increases by about 0.05″ in only 100 days.

9. i Lyr is a B7 IV star first resolved as a binary by Starikova and Tokovinin (1981) who found for 1981.370 $\theta = 67 \pm 2^{\circ}$ and $\rho = 0.075 \pm 0.003''$ with $\Delta m \sim 0.17$. About 100 days later, this system only shows an increasing angular separation without change in position angle.

10. α Del Aa. The brightest component of the double star ADS 14121 was first resolved by Wickes (1975), who gives a magnitude difference in the red of about 2. The primary is classified B9 V-IV. The 16 published observations by speckle interferometry show a variation in position angle of 80° in 7 years.

11. HR 8164. This is the first resolution of the bright component of the wide visual binary ADS 14864. The companion resolved here could be the blue component of the VV Cep system M1 Ib ep + B2 V (Cowley, 1969). Observations by speckle interferometry at various wavelengths will be continued to precise this identification.

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TABLE I. — *Limits of detection for companions in binary systems observed by speckle interferometry.*

RUN	D	ρ ⩾	Δ m ⩽	p
OHP June 1982	1.93	70	2	12
ESO June 1981	3.60	40	2	6.6
CFH June 1980	3.60	35	2	4.4
CFH Mar. 1981	3.60	40	1.5	9.7
CFH Mar. 1982	3.60	30	3	4.4
SAO Sep. 1981	6.00	25	1.5	8

D = diameter of the telescope in meter

ρ ⩾ = limit of resolution in milliarc second at 5500 Å

Δm ⩽ = greater detectable difference of magnitude

p = size of the pixel in the autocorrelation (in milliarc second).

TABLE III. — *Residuals in position angle and angular separation for visual binaries.*

ADS/name	Epoch 1980 +	$(o-c)_\theta$	$(o-c)_p$	Orbit	quality
KUI 23	2.1707	- 53.3	+ 40	Eggen 1962	
		+ 3.2	- 80	Abteral 1963	
		- 15.8	- 24	Stanekova 1981	
7662	1.2365	+ 22.3	+ 89	Finsen 1977	
9019	1.2368	+ 13	- 25	Heintz 1975	
9301	0.4762	+ 1.5	- 3	Van der Bos 1946	a
	2.4541	- 2.1	- 3	"	
	2.4542	- 0.1	- 1	"	
9744	0.4708	+ 1.8	- 5	I Van der Bos 1963	a
	"	+ 1.6	- 15	II " "	"
	1.2426	- 0.9	- 9	I "	
	"	- 0.7	- 24	II "	
	2.4517	- 1.4	- 2	I "	
	"	- 0.5	+ 6	II "	
	2.4519	+ 1.1	- 8	I "	
	"	+ 2.0	+ 0	II "	
10 095	1.2372	+ 20.1	- 17	Heintz 1961	
10 360	0.4709	+ 0.5	- 18	Sester 1963	b
I 1391	1.4989	- 0.8	- 18	Heintz 1972	b
14 773	1.6703	+ 0.9	+ 28	Hans et al 1979	a
	1.6869	- 1.4	+ 24	"	
Cou 14	0.4797	+ 33.4	- 5	Heintz 1972	
Fin 307	1.4856	+ 0.1	+ 7	Churms I 1962	a
	"	+ 0.5	+ 9	" II "	a
15 281	0.4660	+ 4.3	- 10	Couteau et Morel 1971	a

TABLE II. — *Measurements of binary stars.*

HD/ADS	STAR	EPOCH 1980 +	θ(°)	ρ(m")	Télescope	Note
13 530	6 Per	1.6902	47 ± 3	40 ± 5	S.A.O	1
16 739	12 Per	1.6711	206 ± 2	48 ± 5	S.A.O	
		1.6821	202 ± 2	46 ± 5	S.A.O	
		1.6847	200 ± 2	48 ± 5	S.A.O	
		1.6875	201 ± 2	46 ± 8	S.A.O	
16 811	μ Ari	1.6847	78 ± 4	45 ± 5	S.A.O	2
		1.6900	79 ± 4	40 ± 5	S.A.O	
17 878	τ Per	1.6710	81 ± 2	80 ± 5	S.A.O	
18 925	γ Per	1.6711	53 ± 1	284 ± 5	S.A.O	
19 358	β Per	2.1651	142 ± 2	52 ± 5	C.F.H	
34 029	α Aur	1.2361	322 ± 6	40 ± 5	C.F.H	
		1.6822	110 ± 3	40 ± 4	S.A.O	
		2.1624	226 ± 2	55 ± 5	C.F.H	
41 116	1 Gem	2.1707	354 ± 1	128 ± 5	C.F.H	
81 809	HR 3750	2.1683	181 ± 4	33 ± 5	C.F.H	3
ADS 7662		1.2365	187 ± 2	126 ± 10	C.F.H	
	GL 388	1.2446	39 ± 4	78 ± 10	C.F.H	4
107 259	η Vir	0.4735	286 ± 3	85 ± 5	C.F.H	5
		1.2476	308 ± 2	109 ± 10	C.F.H	
		2.1711	330 ± 1	124 ± 5	C.F.H	
ADS 9019		1.2368	118 ± 2	310 ± 10	C.F.H	
ADS 9301		0.4762	26 ± 1	188 ± 5	C.F.H	
		2.4541	355,5 ± 2	170 ± 10	O.H.P	
		2.4542	357,5 ± 2	172 ± 10	O.H.P	
137 909	β Cr B	0.4682	330 ± 2	105 ± 5	C.F.H	6
		1.2427	259 ± 5	40 ± 10	C.F.H	
		2.1661	176 ± 2	115 ± 5	C.F.H	
		2.1742	174 ± 2	118 ± 5	C.F.H	
		2.4543	176 ± 2	144 ± 10	O.H.P	

HD/ADS	STAR	EPOCH 1980 +	θ(°)	ρ(m")	Télescope	Note
ADS 9744	ι Ser	0.4708	71 ± 1	195 ± 5	C.F.H	
		1.2426	70 ± 2	186 ± 10	C.F.H	
		2.4517	73 ± 2	192 ± 10	O.H.P	
		2.4519	75 ± 2	186 ± 10	O.H.P	
143 275	δ Sco	0.4684	163 ± 2	100 ± 5	C.F.H	7
		1.4767	173 ± 2	143 ± 6	E.S.O	
		1.4793	174 ± 2	145 ± 6	E.S.O	
		1.4929	172 ± 2	147 ± 6	E.S.O	
ADS 10095		1.2372	113 ± 3	78 ± 10	C.F.H	
ADS 10360		0.4709	76 ± 2	95 ± 5	C.F.H	
155 763	ζ Dra	1.6867	55 ± 2	96 ± 4	S.A.O	8
ADS 111 49	HR 6814	0.4713	51 ± 1	98 ± 5	C.F.H	
		0.4739	50 ± 1	92 ± 5	C.F.H	
170 153	χ Dra	1.6838	62 ± 3	80 ± 4	S.A.O	
	I 1391	1.4961	140 ± 1	257 ± 7	E.S.O	
178 475	ι Lyr	1.6894	66 ± 2	100 ± 4	S.A.O	9
187 076	δ Sge	2.1718	160 ± 5	37 ± 5	C.F.H.	
196 867	α Del Aa	0.4742	153 ± 1	155 ± 5	C.F.H	10
202 214	HR 8119	1.6896	41 ± 3	65 ± 4	S.A.O	
ADS 14773		1.6703	196 ± 3	128 ± 4	S.A.O	
		1.6869	193 ± 2	120 ± 4	S.A.O	
203 338	HR 8164	1.6869	120 ± 2	96 ± 4	S.A.O	11
205 021	β Cep	0.4743	52 ± 1	180 ± 5	C.F.H	
ADS 15281		0.4660	290 ± 1	180 ± 5	C.F.H	
	Cou 14	0.4797	2 ± 1	175 ± 5	C.F.H	
	Fin 307	1.4856	107 ± 1	166 ± 5	E.S.O	
213 310	5 Lac	0.4661	48 ± 2	109 ± 5	C.F.H	
217 675	ο And	0.4662	6 ± 1	305 ± 5	C.F.H	
		0.4744	5 ± 1	290 ± 5	C.F.H	
218 640	89 Aqr	1.4939	328 ± 1	282 ± 5	E.S.O	

TABLE IV. — *Residuals in position angle and angular separation for speckle interferometric/spectroscopic binaries.*

STAR	DATE 1980+	(O-C) (°) θ	(O-C) (m") ρ	REFERENCE OF THE ORBIT
12 Per	1.6711	-1.0	+2	McAlister, 1978a
	1.6821	-2.7	-2	" "
	1.6847	-4.1	0	" "
	1.6875	-2.4	-2	" "
τ Per	1.6710	-17.2	+20	McAlister, 1981c
γ Per	1.6711	-8.9	+43	McAlister, 1982
β Per	2.1651	-1.0	-14	Bonneau, 1979
α Aur	1.2361	0.0	0	McAlister, 1981a
	1.6822	+0.4	-1	" "
	2.1624	+0.2	+1	" "
χ Dra	1.6838	+3.1	+6	McAlister, 1980

TABLE V. — *Unresolved systems.*

HD	STAR	Epoch 1980 +	Wavelength (Å)	Telescope	Note
3883	HR 178	1.6846	5500	S.A.O	2 - 6a
	Gl 49	1.6846	7500	S.A.O	
		1.6899	"		
8538	δ Cas	1.6899	5500	S.A.O	
11 636	β Ari	1.6900	5500	S.A.O	3 - 6a
17 433	Gl 113	1.6875	7000 - 5500	S.A.O	
18 474	HR 885	1.6901	7000 - 5500	S.A.O	2
20 084	HR 965	1.6902	5500	S.A.O	2
21 754	5 Tau	1.6821	5500	S.A.O	3 - 6a
23 181	o Per	2.1623	7500 - 5500 - 4000	C.F.H	
		2.1650	" " "		
23 288	16 Tau	1.6903	5500	S.A.O	- 6a
23 408	20 Tau	1.6903	5500	S.A.O	- 6a
23 850	27 Tau	1.6822	5500	S.A.O	3 - 6a
25 555	36 Tau	1.6822	7500	S.A.O	2
32 537	Gl 187.2	1.6876	7000 - 5500	S.A.O	- 3
42 995	η Gem A	2.1679	6500 - 4400	C.F.H	3 - 6a
		2.1706	" "		
76 644	ι UMa	2.1791	7500 - 4400	C.F.H	3
79 910	23 Hya	2.1682	5500	C.F.H	3 - 6a
87 737	η Leo	2.1736	5500	C.F.H	1
89 025	ζ Leo	2.1740	5500	C.F.H	1
91 316	ρ Leo	2.1740	5500	C.F.H	1
98 230	ξ UMa	2.1710	5500	C.F.H	4 - 6a
98 991	ι Crt	2.1712	7500	C.F.H	3 - 6a
103 095	Gl 451	0.4735	7900 - 5500 - 4400	C.F.H	
104 321	τ Vir	2.1711	5500	C.F.H	3 - 6a
104 979	o Vir	2.1713	5500	C.F.H	
105 981	4 Com	2.1684	4400	C.F.H	3
106 760	HR 4668	0.4735	7000 - 5500	C.F.H	3 - 6a
112 185	ε UMa	0.4734	7000 - 5500 - 4400	C.F.H	1 - 6a
	ADS 8887 Aa	2.1784	5500	C.F.H	
	Gl 514	2.1714	7500	C.F.H	
121 370	η Boo	0.4679	7000 - 5500 - 4400	C.F.H	3 - 5 - 6a
		0.4762	" " "		
		0.4794	" " "		
		2.1715	7500	C.F.H	"
122 742	Gl 538	2.1714	7500	C.F.H	
131 511	Gl 567	2.1715	7500	C.F.H	
141 004	λ Ser	0.4707	7900 - 5500 - 5000	C.F.H	3 - 6a
141 795	ε Ser	0.4707	5500	C.F.H	
142 983	48 Li 6	2.1688	6500	C.F.H	2
144 208	HR 5983	0.4708	5500	C.F.H	2 - 6a
145 849	HR 6046	0.4708	5500	C.F.H	3
148 856	β Her	0.4708	5500	C.F.H	1 - 3 - 6a
		2.1742	"	"	
151 613	HR 6237	0.4709	7900 - 5500	C.F.H	1 - 3 - 6a
151 769	20 Oph	0.4709	5500	C.F.H	3 - 6a
		2.1716	7500	"	
156 026	Gl 664	2.1716	7500	C.F.H	
157 978	HR 6497	0.4711	5500	C.F.H	2 - 6a
159 571	α Oph	0.4739	7900 - 5500	C.F.H	4 - 6a
		2.1717	7500	"	
160 762	ι Her	0.4711	5500	C.F.H	1 - 6b
		2.1744	7000	"	
186 408	16 Cyg AB	0.4796	7000 - 5500	C.F.H	
		1.6840	7500	S.A.O	
187 076	δ Sge	0.4797	5500 - 4400	C.F.H	1-3-5-6b
187 362	ζ Sge	0.4797	5500	C.F.H	
192 577	o1 Cyg	0.4742	5500	C.F.H	2 - 3 - 5
192 909	o2 Cyg	0.4742	550C - 4400	C.F.H	2-3-5-6a
197 177	49 Cyg AB	1.6871	7000 - 5500	S.A.O	2
212 593	4 Lac	1.6872	7000 - 5500 - 4500	S.A.O	2 - 6a
215 182	η Peg	0.4743	5500 - 4500	C.F.H	1-3-6a-6b

NOTES :

1. Interferometric binary
2. Star with composite spectrum
3. Spectroscopic binary resolvable by interferometric technics (Halbwachs, 1981)
4. Astrometric binary
5. Unresolved binary in Bonneau et al. (1980)

6a. " " in Mc. Alister (1978 c)
6b. " " in Mc. Alister and Hendry (1981 b)