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New binary stars discovered by lunar occultations. IV*

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Abstract. We report on a total of 20 sources observed in the near infrared in the course of routine lunar occultation programs at the TIRGO and Calar Alto observatories. The results consist either in discoveries of new binaries, or in re–observations of known or suspected binaries where only incomplete information was previously available. For the first time, a companion has been detected around the following 6 stars: DO 2779, SAO 162001, SAO 93083, IRC −20444, SAO 162521, and GCVS 980. Additionally, SAO 93746 is discovered to be a triple system, with projected separations at the $0\overset{''}{.}01$ level. For the following 7 stars, our observations confirm previous reports of binarity and provide complementary information in the infrared: SAO 96746-A, SAO 161202, SAO 94060, AG +16 403, SAO 98270, SAO 93950 and SAO 94554. Finally, for the following 4 stars, a companion had been previously observed or suspected, but we could not detect it for various reasons: SAO 96810, SAO 93961, SAO 93975 and SAO 93981. The projected separations in our positive results range from $0\overset{''}{.}01$ to $0\overset{''}{.}57$, and the brightness ratios up to ΔK=4.4 mag. In addition, two visual doubles, namely SAO 184176 and SAO 94002, have also been observed and their projected angular separations and infrared brightness ratios are reported here. This paper is the fourth in a series, bringing to 58 the total number of binary sources studied by our group by means of lunar occultations.

Key words: occultations – stars: binaries: close – stars: binaries: spectroscopic – stars: binaries: visual – astrometry

1. Introduction

This paper follows in a series of reports (see Richichi et al. 1994, 1996 and 1997, hereafter Papers I, II and III), on discoveries of new binary stars, or on re-observations of known systems. The data were collected in the course of two long-term routine programs of lunar occultations (LO) in the near-IR, which have been active for a number of years at the TIRGO and Calar Alto observatories. We refer the reader to Paper II for a detailed description of our observational and data reduction methods, and of the instruments and telescopes used.

The observations log is reported in Table 1, following the same format of Paper III. In summary, Columns (1) through (3) list the source identification, the date of the event and the telescope used. In this latter column, the symbols identify the telescopes: T for the 1.5 m TIRGO telescope, and C1, C2 for the Calar Alto 1.23 m and 2.2 m telescopes respectively. In all cases InSb photometers equipped with broad band K filters were used. The characteristics of the acquisition systems and filters are described in Paper II. Column (4) lists the aperture of the diaphragm, while Columns (5) and (6) list the sampling time of the lightcurves, and the integration time for each data point where applicable. Columns (7) and (8) list the total magnitude of the star in the V and K filters. The V magnitudes are taken from the literature, while the K magnitudes are from our own photometric data except in the case of three sources, for which we present an estimate based on the expected V–K color for the given spectral type. In Columns (9) and (10) we report the spectral types and distances, again extracted when available from the literature; in the case of multiple determinations, the most frequent or most recent were used. The distances are based on Hipparcos parallaxes. Finally, the last column reports a short comment on whether the binary was previously known or not. Table 2 lists the cross–identifications of the observed sources. In two cases, no cross-identification with other catalogues could be established, and we provide coordinates from the HST Guide Star Catalogue.

2. Stars with positive binary detection

The stars for which we could positively detect a companion are listed in Table 3, where the entries follow the style introduced in Paper I. In particular, the columns list the absolute value of the fitted angular rate of the event V in ″/s, its deviation from the predicted rate V_t as computed by us, the local lunar limb slope ψ, the true position and contact angles, the signal–to–noise ratio (SNR), the projected separation, the brightness ratio and finally the K magnitudes of the two components in each star, based on the values given in Table 1. A more detailed explanation and discussion of these quantities is given in Paper II. In the

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* Based on observations collected at TIRGO (Gornergrat, Switzerland), and at Calar Alto (Spain). TIRGO is operated by CNR–CAISMI Arcetri, Italy. Calar Alto is operated by the German–Spanish Astronomical Center.

Table 1. List of the occultation events and the circumstances of their observation

(1) Source	(2) Date UT	(3) Tel.	(4) D ″	(5) Δt ms	(6) τ ms	(7) V mag	(8) K mag	(9) Sp.	(10) Dist. pc	(11) Notes
DO 2779	25-02-94	C1		2.0	—		3.67	M0		new detection
SAO 184176	18-07-94	C2		2.0	—	8.5	3.43	M0III		visual double star
SAO 94002	13-10-95	T	21	2.4	2.0	6.3	5.75	B9IVn	130	visual double star
SAO 162001	03-06-96	C2		2.0	—	6.6	4.4[a]	G8/K0III	134	new detection
SAO 93083	20-12-96	T	14	2.9	2.5	5.2	4.67	A7III-IV	38	new detection
SAO 96746	17-03-97	T	28	2.9	2.5	3.6	3.27	A3V	29	multiple star; occultation binary
SAO 96810	17-03-97	C1		2.0	—	8.6	5.52	K2V		occultation binary; no detection
IRC −20444	14-08-97	C1		2.0	—		1.58	M9		new detection
SAO 161202	14-08-97	T	28	5.4	5.0	9.3	8.4[a]	F2/F3V		speckle binary
SAO 162521	16-08-97	C1		2.0	—	5.9	3.6[a]	K0III	110	new detection
SAO 93746	08-01-98	T	21	3.9	3.5	7.8	5.13	G5	282	new detection, triple
SAO 94060	05-02-98	T	28	3.4	3.0	8.6	7.39	F5		speckle binary
AG +16 403	05-02-98	T	21	3.9	3.5	9.5	6.64	K0	42	spectroscopic binary; speckle binary
SAO 98270	09-03-98	T	21	2.9	2.5	8.1	5.39	K0		speckle binary
SAO 93950	05-11-98	T	28	2.4	2.0	5.0	2.25	K2III	60	occultation binary; no detection
SAO 93961	05-11-98	T	28	1.9	1.5	6.6	5.21	F8	49	speckle binary; no detection
SAO 93975	05-11-98	T	21	2.4	2.0	4.8	4.21	A6IV	44	occultation binary; no detection
SAO 93981	05-11-98	T	21	2.4	2.0	6.5	5.27	F2	41	occultation binary; no detection
SAO 94554	06-11-98	T	21	2.4	2.0	5.4	5.65	B5V	205	occultation binary
GCVS 980	06-11-98	T	21	3.4	3.0		5.44			new detection
SAO 93950	30-12-98	C1		2.0	—	5.0	2.25	K2III		occultation binary; repeat observation

a) value estimated from the V magnitude and the expected color for the given spectral type

Table 2. Cross identifications

SAO	HD	Other Identifications	
SAO 184176	HD 145029	ADS 9936 AB	
SAO 94002	HD 28867	ADS 3297 AB	HR 1442
SAO 162001	HD 175453		
SAO 93083	HD 17093		HR 812
SAO 96746	HD 56537	ADS 5961 A	54 Gem
SAO 96810	HD 57339		
		IRC −20444	18090-1853
SAO 161202	HD 167034		
SAO 162521	HD 181645		HR 7344
SAO 93746	HD 25584	AG +14 357	04013+1453
SAO 94060	HD 29562	ADS 3371 AB	AG +16 402
	HD 29608	AG +16 403	
SAO 98270	HD 76793	ADS 7117 AB	AG +14 970
SAO 93950	HD 28292	IRC +20079	HR 1407
SAO 93961	HD 28363	ADS 3248 AB	AG +16 379
SAO 93975	HD 28527	AG +16 384	HR 1427
SAO 93981	HD 28568	AG +16 385	
SAO 94554	HD 35671	AG +17 489	HR 1808
Source	GSC Coordinates (2000.0)		
DO 2779	α=09:32:10.4	δ=+08:54:24	
GCVS 980	α=05:33:01.7	δ=+18:07:58	

following, we have tried to assign a spectral type to the companions, on the basis of the spectrum of the primaries and of the observed difference in magnitude. This was done on the basis of our observed ΔK only. In principle, it should be possible to put better constrains on the spectral types by including Δm values at other wavelengths when available, but we note that in the case of previous speckle measurements this information is often missing, while in the case of previous LO measurements the adopted filters were often significantly different from the standard ones. Therefore, this task would require detailed computations using synthetic spectra and filter transmissions, which we did not attempt.

2.1. SAO 162001

A companion has been detected for the first time around this star with a projected angular separation $\rho_{\rm P}$=36 milliarcseconds (mas), and ΔK=3.4 mag. We constrain the spectral type of the companion to be an early F dwarf. This source was observed earlier in the visual by LO, but the companion was not detected (Edwards et al. 1980).

2.2. SAO 96746

SAO 96746 is a multiple system with a large angular separation of ≈10.″0 between components A and B. Component A was reported as an occultation binary by Dunham (1977), with $\rho_{\rm P}$=45 mas and PA=300°. After this, several attempts by LO (Africano et al. 1978; Eitter & Beavers 1979) and speckle observations (Hartkopf & McAlister 1984), all at visual bands, failed to confirm the detection. Our earlier attempt by LO in the near-IR (Paper II) was also negative, and we speculated that the companion might have had a significant orbital motion in the time since Dunham's original detection. Now we are able to confirm the companion component A from the observations reported here. We find $\rho_{\rm P}$=14 mas along PA=120°, and ΔK=3.4 mag. By coincidence, our measurement occurred exactly as the same position angle of Dunham's occultation, although in the opposite direction: this confirms the fact that the companion must have an orbit which changes its position significantly over 20 years. Our previous negative detection can be explained by a combination of this effect, and the large ΔK of the companion.

2.3. IRC −20444

We detect for the first time a companion around this late-type star, with $\rho_{\rm P}$=28 mas and ΔK=2.8 mag. The spectral type of the companion can be constrained either to an early M giant or to an early O main sequence star. The stellar disk of the primary component was also resolved from our observations, and the results are reported in Richichi et al. (1998).

2.4. SAO 161202

This sub-arcsecond binary was resolved earlier by LO (Evans & Edwards 1981), and subsequently by speckle (Mason 1996). Our observations yield $\rho_{\rm P}$=178 mas along PA=94°, and ΔK=0.07 mag. The companion is likely to be of similar spectral type as that of the primary component.

2.5. SAO 162521

A companion has been detected around this star for the first time with $\rho_{\rm P}$=21 mas and ΔK=3.1 mag. The spectral type of the companion can be constrained to around A5 dwarf. This source was repeatedly observed earlier by LO in the visual, but the companion was never detected (Africano et al. 1976; Eitter & Beavers 1979; Morbey et al. 1978). The angular diameter of the primary component was derived to be 6.5±0.5 mas, based on a model fit to the first diffraction fringe of a visual occultation lightcurve (Morbey et al. 1978). These authors also mentioned that a point source model fitted well the other fringes. Our observation rules out the possibility of such a large angular size for the primary.

2.6. SAO 94060

SAO 94060 was observed with negative results by earlier LO observations in the visual (Evans & Edwards 1981; Radick & Lien 1982), but was subsequently resolved by speckle (McAlister et al. 1987; McAlister et al. 1989). These latter authors report angular separations and position angles at several epochs. Our observation provides $\rho_{\rm P}$=567 mas along PA=59°, and ΔK=0.9 mag. We constrain the spectral type of the companion to be around G2, but we also note that using Δm from Hipparcos a type close to G8 is inferred.

2.7. AG +16 403

This star is a member of the Hyades cluster and is a spectroscopic binary with a period of 277 days, as reported by Griffin et al. (1985). A companion to AG +16 403 was also detected by speckle interferometry by Mason et al. (1993), who however recognized that the speckle component, at a separation of $0\farcs659$, is not the spectroscopic binary. In fact, they assign to the speckle binary a period of 167 years. Also our LO detected companion has a relatively large projected separation, $\rho_{\rm P}$=241 mas, and presumably it is not the spectroscopic but rather the speckle binary, also dubbed CHARA 154. However, after taking into account the position angles, we note that our result is not completely consistent with that obtained by speckle, at least under the assumption that the period is indeed much longer than the 6.2 years that separated the two measurements. We also note that in their original work, Griffin et al. (1985) mentioned that the analysis of the spectroscopic data for this system showed systematic anomalies that could not be well accounted for, and that their solution was only tentative. In the light of the more recent speckle and LO measurements, it might be worthy to investigate again the radial velocity data for this triple system. With a ΔK=1.0 mag, the spectral type of the speckle/LO companion can be constrained to a late K dwarf.

2.8. SAO 98270

SAO 98270 is a speckle binary (Hartkopf et al. 1997), for which we derive a projected angular separation $\rho_{\rm P}$=177 mas and ΔK=0.6 mag. The spectral type of the companion can be constrained to be around K5.

2.9. SAO 94554

SAO 94554 is a member of Pleiades group and a LO binary (Africano et al. 1978; Evans & Edwards 1981; Radick et al. 1982). Subsequently, the system has been studied extensively by speckle (McAlister & Hendry 1982; McAlister et al. 1989; McAlister et al. 1990; Mason 1996; Hartkopf et al. 1997; Fu et al. 1997). Recently, a binary orbit for this occultation binary has been published by Mason (1997), with a period of 15.38 yrs. The spectral type of the companion has been suggested by different authors to be between B8V and A0V. Our observation in the near-IR yields $\rho_{\rm P}$=15 mas, in good agreement with the orbit computed by Mason (1997), and a ΔK=1.0 mag. This latter value leads us to assign a spectral type close to B9V for the companion. This is in agreement with previous estimates, but it leaves open the matter of the high combined mass for this system, as noted by Mason (1997).

2.10. SAO 93950

SAO 93950 was reported as a possible LO binary with a projected angular separation of 24 mas along PA=238° and Δm=2.5 in a wide Hβ filter by Fekel et al. (1980). However, there was no confirmation in spite of several other LO (Morbey et al.

Table 3. Summary of binary detection results

(1) Source	(2) $\lvert V \rvert$	(3) V/V$_t$−1	(4) ψ	(5) PA	(6) CA	(7) SNR	(8) Sep. (mas)	(9) Br. Ratio	(10) m_1	(11) m_2
DO 2779	0.3628	3%	$3°$	$87°$	-32°	47.2	395 ± 26	24.0 ± 1.7	3.7	7.2
SAO 184176	0.3383	−5%	$-4°$	$60°$	$-34°$	43.5	3405 ± 7.1	53.8 ± 3.4	3.4	7.8
SAO 94002	0.2139	−2%	$-1°$	$312°$	$232°$	5.3	2283 ± 21	1.57 ± 0.04	6.3	6.8
SAO 162001	0.3778	12%	$8°$	$232°$	$144°$	60.5	36.0 ± 0.6	23.7 ± 0.9	4.4	7.9
SAO 93083	0.1685	11%	$3°$	$9°$	$-64°$	22.1	35.5 ± 2.2	11.2 ± 0.4	4.8	7.4
SAO 96746-A	0.3387	−5%	$-6°$	$120°$	$17°$	70.5	14.1 ± 0.7	23.8 ± 0.9	3.3	6.8
IRC −20444	0.1536	0%	$0°$	$26°$	$-66°$	32.3	28.1 ± 1.8	13.1 ± 0.1	1.7	4.5
SAO 161202	0.4099	0%	$0°$	$94°$	$7°$	3.3	177.8 ± 1.9	1.07 ± 0.08	9.1	9.2
SAO 162521	0.3228	−15%	$10°$	$106°$	$29°$	14.7	20.6 ± 9.5	16.8 ± 1.1	3.7	6.7
SAO 93746 A-B	0.3834	0%	$0°$	$116°$	$34°$	20.0	11.0 ± 0.6	6.32 ± 0.53	5.4	7.4
SAO 93746 A-C							25.9 ± 0.8	9.98 ± 0.89	5.4	7.9
SAO 94060	0.3669	0%	$0°$	$59°$	$-22°$	12.8	567.3 ± 6.5	2.22 ± 0.25	7.8	8.7
AG +16 403	0.3907	2%	$5°$	$70°$	$-11°$	6.0	241.3 ± 1.8	2.58 ± 0.10	7.0	8.0
SAO 98270	0.2667	0%	$0°$	$66°$	$-41°$	6.1	177.0 ± 7.5	1.72 ± 0.08	5.9	6.5
SAO 94554	0.5655	1%	$8°$	$275°$	$196°$	11.7	14.7 ± 1.1	2.53 ± 0.16	6.0	7.0
GCVS 980	0.4621	3%	$8°$	$254°$	$174°$	16.8	81.8 ± 1.4	15.5 ± 1.1	5.5	8.5
SAO 93950	0.4619	2%	$3°$	$55°$	$-15°$	34.1	25.5 ± 2.5	79 ± 19	2.3	7.0

1978; Evans & Edwards 1981; Radick & Lien 1982; Radick et al. 1982), as well speckle observations (Hartkopf & McAlister 1984; Mason 1996), all in the visual. We obtained two measurements of this source, the second of which confirms the companion. It is interesting to note that our positive detection occurred at a PA almost identical (see Table 3) to that of the event which lead to the discovery by Fekel and co-authors. This is not surprising, since the two observations are separated by almost exactly one Saros cycle, and the stations are at very similar latitudes. It is more intriguing the fact that we obtained also the same separation as in the original detection, but in the opposite direction. It would then appear that the companion has undergone a substantial orbital motion.

We note that the SNR value reported in Table 3 could give the impression of a detection below the noise level. In fact, this is a global value which incorporates the effect of atmospheric scintillation. The disappearance of the companion occurred after that of the primary, i.e. in a portion of the lightcurve where the SNR was close to 100. Reversely, the negative detection in our first observation, in spite of a formally higher SNR, can be explained by noting that one half of the first trace is affected by scintillation at a level which is larger than the magnitude of the companion. Also, our first and second events occurred along almost orthogonal position angles, and it is possible that the projected separation during the first event could have been too small for detection by our technique. The observed ΔK=4.7 mag is consistent with a spectrum close to F2V for the companion.

Note also that the angular diameter of this star was derived in the visual and near-IR, with values of 1.63$\pm$1.07 mas and 2.27$\pm$0.24 mas respectively (White & Feierman 1987; Ridgway et al. 1982). Given the large brightness ratio, the influence of the companion on such measurements should be negligible. Also our measurements resolve the disc of the primary, and we will report our value for the angular diameter of this star elsewhere.

2.11. Remaining stars

There is no literature available for DO 2779, SAO 93083, SAO 93746, GCVS 980. Our lightcurves reveal a companion around these sources for the first time, with the parameters listed in Table 3. We note that SAO 93746 is best fitted by a triple star model, as shown in Fig. 1.

The last two stars, SAO 94002 and SAO 184176, are visual doubles with angular separations exceeding one arcsecond, and are reported here only for completeness. A rich amount of astrometric observations are available for SAO 94002 (Thé 1975; Jeffers & Vasilevskis 1978; Pannunzio & Morbidelli 1983; Jasinta et al. 1995). Both components of this well separated double system have been searched for multiplicity by speckle observations in the visual, with negative results (Mason 1996). There is no literature available on SAO 184176.

3. Stars with negative binary detection

The stars for which we could not detect a companion are listed in Table 4. To facilitate a comparison with previous reports of a companion, we list the true PA of our observation in Column (3); this includes the limb slope ψ measured from the fringe speed, listed in Column (2). The SNR of the data, listed in Column (4), gives an indication of the minimum magnitude difference of a companion that would have been consistent with our data. In Column (5), we list the possible reason for non–detection by us. The case of SAO 93950 has already been discussed in Sect. 2.10.

3.1. SAO 96810

SAO 96810 is a spectroscopic binary, with a period of 7.25 years (Pédoussault et al. 1988). A companion was detected from our earlier observation (Paper III), but we do not detect it from the data reported here. Insufficient SNR is a good explanation, the

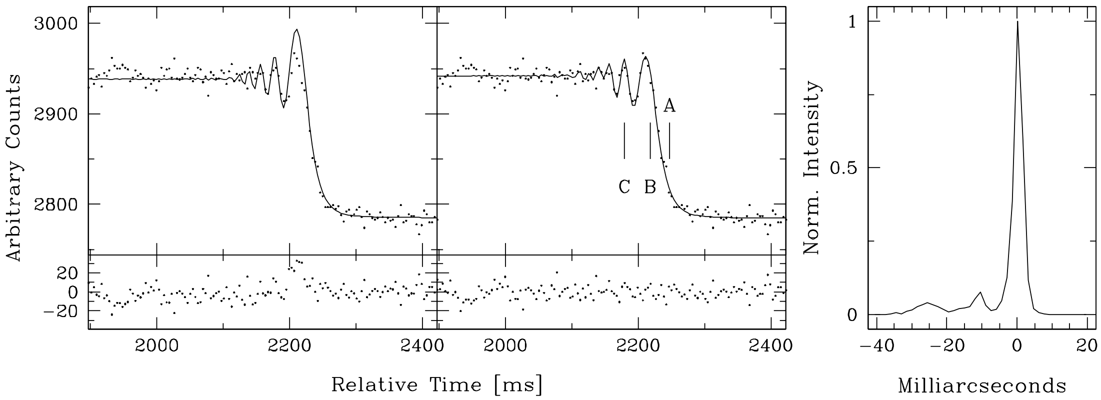

Fig. 1. Example of a new detection, the triple star SAO 93746. *Left*: Occultation data (dots), and best fit (solid line) by a single point source model. The residuals are shown in the lower panel. *Center*: Same, for a model with three point sources (see parameters in Table 3). The occultation times of the three components are marked. *Right*: Brightness profile, reconstructed by a model–independent method (see Paper II).

companion being about 2 mag fainter than the primary in the K band. The companion was resolved earlier also by Edwards et al. (1980), while other LO (Africano et al. 1977; Eitter & Beavers 1979) and speckle observations (Mason 1996) in the visual failed to detect it.

3.2. SAO 93961

SAO 93961 belongs to the Hyades cluster, and is a well studied sub-arcsecond binary with an orbital period of 40.4 yrs. A long list of LO observations of this source in the visual are listed in Evans (1984), who infers the spectral type of the secondary to be F9V. This source has been observed repeatedly also by speckle in the visual (see for instance Hartkopf et al. 1997), and more recently in the near-IR (Patience et al. 1998). Our negative detection is most likely due to the fact that our lightcurve partially fell in a gap between two blocks of data (see Paper I).

3.3. SAO 93975

SAO 93975 is a LO binary with a projected angular separation of ≈10 mas at PA=284° and ≈5 mas at PA=86° (Peterson et al. 1981). These authors suggest a G0V spectral type for the companion. Also Radick & Lien (1980) have reported this star to be double, however the companion was not detected in several other LO (White 1979; Evans & Edward 1981; Fekel et al. 1980; Radick & Lien 1982; Radick et al. 1982), as well as speckle observations (Mason et al. 1993; Mason 1996), all in the visual. We could not detect the companion either. As for SAO 93961 above, our lightcurve partially fell between two data blocks and hence our negative result is not conclusive.

3.4. SAO 93981

This star is a suspected LO binary with $\rho_{\rm P}=0.''929$ along PA=292° (Radick & Lien 1982). It is unlikely that we could fail to detect such a wide companion in our observation, unless it had a much higher brightness ratio in the near-IR than the 1 mag reported in the visual. However, we also note that many other observers have failed to detect it both by LO in the visual (Radick et al. 1982; Evans & Edwards 1981; Peterson et al. 1981), as well as by speckle in the visual and near-IR (Mason et al. 1993; Mason 1996; Patience et al. 1998).

Table 4. Summary of negative detection results

(1) Source	(2) ψ	(3) PA	(4) SNR	(5) Notes
SAO 96810	0°	74°	3.9	insufficient SNR
SAO 93950	22°	328°	41.0	scintillation
SAO 93961	0°	252°	8.0	data gap
SAO 93975	6°	244°	26.5	data gap
SAO 93981	0°	225°	11.1	not a binary?

4. Conclusions

We have reported on lunar occultation observations of 20 binary stars carried out in the near-IR. A companion has been detected for the first time around 7 sources, one of them being in fact a triple star; additionally, our observations confirm previous reports on binarity and provide additional information in the infrared for other 7 stars. We do not detect a previously known or suspected companion around 4 stars, and we provide a possible explanation in each of the cases. Finally, two of the stars are visual binaries.

Summing up the results presented here with those reported earlier in Paper I, II and III, a total of 58 binary stars have been observed so far in the course of our LO program. The stars reported were extracted from a sample of 185 lunar occultations, yielding a binary frequency in our (biased) target lists of ≈11%, which is consistent with similar statistics described in our previous papers.

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