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New binary stars discovered by lunar occultations. V*

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Abstract. We present recent results from our ongoing lunar occultation program on binary stars at the TIRGO and Calar Alto observatories. Observations are presented here for a total of seventeen sources, the majority of which are resolved for the first time. These include SAO 94621, IRAS 18154-1900, SAO 98345, SAO 98363, SAO 93947, SAO 97319, SAO 97437, SAO 94986, SAO 94488, DO 11742, SAO 78027 and SAO 79799. Two speckle binaries were also observed, namely SAO 98427 and SAO 110723; this latter is discovered to be a quadruple system. SAO 77810 is found to be a new triple system. In the cases of SAO 94621 and SAO 98363, we have recorded two occultation light curves each, at different position angles: this allowed us to derive actual position angles and separations for these binary systems. We report an observation of the occultation binary SAO 94961, for which we could not detect the companion. Finally, we report also an observation of the well-studied multiple system SAO 97645 (ζ Cnc), which is discussed in detail in a separate paper.

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

1. Introduction

A program of lunar occultations (LO) in the near infrared has been carried out for more than a decade at the TIRGO and Calar Alto observatories. Close binaries among field stars are one of the aims of the program. Several results have been previously reported in a series of papers: see Richichi et al. 1994, 1996a, 1997 and 1999 (hereafter Papers I, II, III and IV). They include the discovery of new binary systems, or the re-observation of known ones for which only partial information was known. This paper continues the series, adding observations for 17 sources. Details on the telescopes, instrumentation and data reduction procedures can be found in Paper II.

Table 1 lists the observational parameters of the observed sources, in the same format as 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 equipped with the FIRT photometer, and C1 for the Calar Alto 1.23 m telescope equipped with the FIRPO photometer. The primary mirror of this latter telescope was partially covered during the observations reported here, to cover some surface defects. The resulting collecting surface was equivalent to a 70 cm clear diameter only. In all cases, broad band K filters were used. The characteristics of the acquisition systems and filters are described in Paper II. Column (4) lists the diaphragm aperture, while Columns (5) and (6) list the sampling time of the lightcurves, and the integration time for each data point in the case of FIRT. 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. The K magnitudes are from our own photometric data when available, or are otherwise estimated as indicated. 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 was used. The distances are based on Hipparcos parallaxes, when available, with values affected by a large uncertainty being listed in parentheses. Distance values preceded by a colon are our own estimates. These latter were obtained from the magnitude and spectral type, and by assuming the luminosity class of a giant star. These distance estimates are very approximate, and should be taken only as an order-of-magnitude indication. Finally, the last column reports a short comment on the nature of the detection. Table 2 lists the cross–identifications of the observed sources.

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

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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
SAO 94621	14-10-95	T	21	2.4	2.0	9.3	4.1	K7	:830	new detection
IRAS 18154-1900	14-08-97	C1	24	4.0	–		6.2[a]			new detection
SAO 94961	10-01-98	T	14	3.9	3.5	7.6	6.4	F5II	(670)	LO binary; no detection
SAO 94621	06-11-98	T	21	3.4	3.0	9.3	4.1	K7	:830	repeated observation
SAO 97645	07-12-98	C1	24	2.0	–	5.1	3.5	F8V	26	multiple star
SAO 98345	08-12-98	T	28	5.4	5.0	9.0	4.9	M3III	:830	new detection
SAO 98363	08-12-98	C1	24	2.0	–	7.7	3.4	M..	(2040)	new detection
SAO 98363	08-12-98	T	28	5.4	5.0	7.7	3.4	M..	(2040)	repeated observation
SAO 98427	08-12-98	C1	24	2.0	–	6.8	4.8	G9V	20	speckle binary
SAO 93947	30-12-98	C1	24	2.0	–	8.2	4.6	K2	:350	new detection
SAO 97319	26-11-99	T	21	4.4	4.0	8.0	4.7	K5	:440	new detection
SAO 97437	27-11-99	T	21	5.4	5.0	9.2	6.8	K0	:500	new detection
SAO 110723	15-01-00	T	21	5.4	5.0	4.2	3.4[a]	F0IV	26	speckle binary; new detection
SAO 94986	19-01-00	T	14	7.5	7.0	5.9	6.4	B2V	430	spectr. binary; new detection
SAO 94488	14-02-00	T	14	10.0	10.4	7.7	5.4	G0	(710)	Hipparcos binary?
DO 11742	13-03-00	T	21	2.5	2.9	8.6	3.8	M1	:660	new detection
SAO 77810	13-03-00	T	21	3.1	3.5	8.9	5.0	K7	:700	new detection
SAO 78027	13-03-00	T	21	3.1	3.5	8.8	4.3	K7	:660	new detection
SAO 79799	15-03-00	T	14	2.9	2.5	5.4	5.4[b]	A0Vs	104	new detection

[a] value estimated from the signal level during the LO event.
[b] value estimated from the V magnitude and the spectral type.

the K magnitudes of the two components in each star, based on the values given in Table 1. A colon in Column (3) denotes cases in which the observed rate leads to a formal value of the contact angle which is not real. However this occurred in one case only, in which the contact angle was close to 0°: under this situation, even a small error in the predicted rate can mimic a large limb slope. In this case, we have assumed the maximum limb slope compatible with a real contact angle. A more detailed explanation and discussion of the quantities in Table 3 is given in Paper II.

In the following, for each of the stars with a positive binary (or multiple) detection we discuss our result and its implications. Where possible, we constrain the spectral type of the detected companions from its absolute K magnitude, which in turn is estimated from the spectral type and the luminosity class of the primary component and the measured ΔK value. In cases where the luminosity class of the primary is uncertain, we attempt to infer it from the observed V-K color and the estimated distance.

Table 2. Cross identifications

SAO 94621	HD 244538	IRAS 05289+1811
IRAS 18154-1900	$18^h\ 18^m\ 21\overset{s}{.}4$	-18° 58′ 54″ (2000.0)
SAO 94961	HD 39455	BD +18 1001
SAO 97645	BD +18 1867	ζ Cnc
SAO 98345	HD 77774	IRAS 09023+1523
SAO 98363	HD 78011	IRAS 09035+1528
SAO 98427	HD 79096	HR 3650
SAO 93947	HD 28293	IRAS 04254+1611
SAO 97319	BD +19 1855	IRAS 07492+1935
SAO 97437	BD +19 1892	
SAO 110723	HD 17094	SBC 99
SAO 94986	HD 39698	57 Ori
SAO 94488	HD 34926	IDS 05158+1848A
DO 11742	BD +20 1185	IRAS 05539+2006
SAO 77810	HD 249916	IRAS 05562+2009
SAO 78027	HD 252208	BD +20 1276
SAO 79799	HD 64648	HR 3086

2.1. SAO 94621

We detect for the first time a companion around this late-type star from two occultation events separated by about three years. Under the assumption that the orbital period of the system is much longer than this time interval, we determine the actual position angle and separation in the plane of the sky to be 121° and 147 mas respectively. Given the large time interval, the formal errors on these values are not meaningful. The spectral type of the companion can be constrained to be around M2. This source was observed earlier in the visible by LO, but the companion was not detected (Africano et al. 1978, Evans & Edwards 1981, Radick et al. 1982).

The parameters derived for this binary system at the two epochs of observation are listed in Table 3. It can be noted that the brightness ratio of the companion differs by about a factor of 2 in the two cases, but this is not necessarily an indication of variability, expecially since in one of the two measurements the SNR is barely sufficient for the detection. However, we note that we obtained K-band photometry of SAO 94621 from TIRGO

Table 3. Summary of binary detection results

(1) Source	(2) |V|	(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
SAO 94621	0.5448	18%	10°	56°	121°	39.6	62.1±2.5	56.51±7.02	4.1	8.5
IRAS 18154-1900	0.7645	−1%	−2°	74°	−10°	2.2	75.7±12.7	5.96±1.15	6.4	8.3
SAO 94621	0.8713	:8%	17°	79°	0°	50.8	109.4±2.3	25.85±1.79	4.1	7.7
SAO 98345	0.7558	1%	−1°	83°	162°	20.8	160.6±1.5	15.92±0.71	4.8	7.8
SAO 98363	0.7496	−1%	2°	87°	166°	20.9	34.6±1.5	11.51±0.13	3.5	6.1
SAO 98363	0.7481	3%	9°	136°	185°	34.6	16.1±0.4	8.30±0.32	3.5	5.8
SAO 98427	0.6780	1%	1°	112°	180°	6.2	54.9±0.2	1.11±0.01	5.5	5.6
SAO 93947	0.8465	2%	8°	70°	0°	9.7	73.5±0.8	16.08 ±1.11	4.7	7.7
SAO 97319	0.8185	8%	9°	71°	159°	34.6	8.8±0.3	7.06±0.33	4.8	7.0
SAO 97437	0.7849	5%	0°	99°	180°	7.1	11.3±1.1	2.94±0.47	7.1	8.3
SAO 94986	1.0545	4%	10°	110°	20°	11.9	15.6±0.7	2.96±0.27	6.7	7.9
SAO 94488	0.4704	−13%	−6°	129°	43°	34.6	12.7 ± 0.9	11.96 ± 0.84	5.5	8.2
DO 11742	0.7220	0%	0°	278°	17°	61.2	5.00±0.09	2.39±0.05	3.8	4.7
SAO 78027	0.7911	8%	6°	58°	−34°	40.1	16.8±0.3	12.13±0.44	4.1	6.8
SAO 79799	0.8817	0%	0°	68°	−22°	7.1	40.5±0.5	1.64±0.07	5.9	6.5
triple										
SAO 77810 A-B	0.7050	0%	1°	102°	18°	30.6	19.4 ± 2.0	11.1 ± 0.7	5.1	7.7
SAO 77810 A-C				102°		29.8	44.1 ± 2.3	16.5 ± 1.2		8.1
quadruple										
SAO 110723 A-B	0.8354	4%	11°	243°	−7°	73.0	7.0±0.1	7.13 ±0.20	3.7	5.9
SAO 110723 A-C				63°		73.8	251.0±0.2	8.73±0.09		6.1
SAO 110723 A-D				243°		70.0	21.0±0.2	11.4 ±0.30		6.4

at four epochs between March 1996 and March 2000, and that variability seems indeed present at least for the system as a whole. The measured values were between K=3.8 and 4.5 mag. The value of K=4.1 listed in Table 1 is a weighted average. We also note that it implies a color V–K ≈5.2, which is significantly redder than expected for a K7 star.

2.2. SAO 97645

This bright star (ζ Cnc) is a well-studied multiple system. It is formed by SAO 97645 and SAO 97646 at about 8″ distance: we recorded the LO of both, and for simplicity we use the first SAO number only. Given the importance of this system, a detailed discussion is presented in a separate paper (Richichi 2000). For this reason, we omit SAO 97645 from the list of results given in Table 3. However, it is included for completeness in Tables 1 and 2, and in the general discussion presented in Sect. 4.

2.3. SAO 98363

We observed an occultation of SAO 98363 on the same date from both TIRGO and Calar Alto. We detect for the first time a companion around this star, with the parameters listed in Table 3. From these measurements, we can derive the actual separation and position angle in the plane of the sky to be 35.5 ± 1.8 mas and $73.^\circ0 \pm 1.^\circ5$ respectively. We have obtained K-band photometry for this source at 3 epochs between March 1999 and March 2000, showing no significant variability.

2.4. SAO 98427

SAO 98427 is a spectroscopic binary (Griffin & Griffin 1982). Our observations yielded the parameters listed in Table 3, and the spectral type of the companion can be constrained to be an early K dwarf. SAO 98427 has been the target of extensive speckle observations in the visible, with results published by McAlister 1977, McAlister et al. 1983, Bonneau et al. 1984, Bonneau et al. 1986, McAlister et al. 1987, Tokovinin & Ismailov 1988, McAlister et al. 1989, McAlister et al. 1990, Hartkopf et al. 1993, McAlister et al. 1993, Balega et al. 1994, Mason et al. 1996, McAlister 1996, Fu et al. 1997, Hartkopf et al. 1997. Mason et al. (1996) refined the orbital parameters of this binary system based on astrometric and spectroscopic data and the orbital period is 987.9 days. The agreement between our measurement and the predicted position based on this orbital elements is very good. Recently, SAO 98427 was resolved by adaptive optics observations (Barnaby et al. 2000), who determined a magnitude difference in the red (Δm=0.12) very close to our determination at 2.2 μm. These authors conclude that the secondary is a K1 dwarf. This source was also resolved by LO in the visible (Meyer et al. 1995).

2.5. SAO 110723

SAO 110723 is a variable star of δ Sct type. It is a single-line spectroscopic binary of period 1202.2 days (Trimble 1969), as well as a suspected speckle binary (Tokovinin 1985). This source was extensively searched for a companion. Tokovinin & Ismailov (1988) gave an upper limit of $0.''06$ and later Ismailov

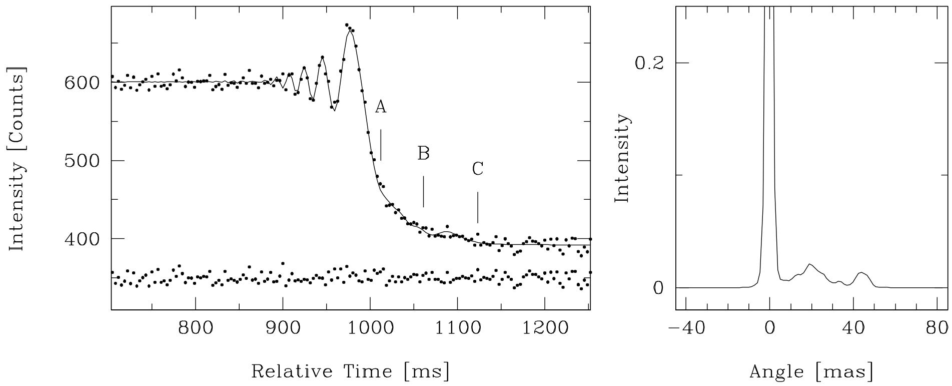

Fig. 1. Example of a new detection, the triple star SAO 77810. The left panel shows the least squares best fit (solid line) to the occultation data (dots). The trace at the bottom are the fit residuals, shifted by an arbitrary offset. The panel on the right shows the brightness profile of the source, as reconstructed by a model-independent method (Richichi 1989). The y-axis is enlarged, to evidentiate the secondary peaks corresponding to the companions.

(1992) reported three resolved measurements with angular separation in the range $0\farcs047$ to $0\farcs116$ and a magnitude difference of about 1.5 mag between the components in the visible. However, this source was unresolved from several other speckle observations (McAlister 1978, Bonneau et al. 1984, Hartkopf & McAlister 1984, Isobe 1991).

We report for the first time that SAO 110723 is a quadruple system, with the parameters reported in Table 3.

2.6. *SAO 94986*

We detect for the first time a companion around SAO 94986. This is a double-lined spectroscopic binary (Pedoussaut & Ginestet 1971). According to the orbital parameters listed by these authors, we should have observed the system at phase 0.91. A comparison of the LO result with the spectroscopic parameters is simplified by the geometry of the system: the eccentricity of the system is small ($e = 0.01$), and the fact that $m_1 \sin^3 i = 8.9 \mathrm{M}_\odot$ is close to the lower mass limit expected for the B2V primary (Allen 1973) indicates that the orbital inclination should be close to $90°$. Under these conditions, we can make an approximate prediction of the maximum expected separation at the time of the LO observation (JD=2451562.61), as the ratio of the sum of the predicted radial velocities to K_1+K_2, times $(a_1 + a_2) \sin i$. The result is 12.7 mas, which is comparable (within the approximations) to the LO-measured separation listed in Table 3. Therefore it would seem that the LO PA happened to be close to the real PA of the system at the time of the observation.

We conclude that we have detected the spectroscopic companion. This conclusion is also supported by the consistency of our brightness ratio with the double-lined nature of the spectroscopic binary. This source was observed earlier in the visible by LO, but with negative results (Eitter & Beavers 1979, Blow et al. 1982).

2.7. *SAO 94488*

This star forms the wide binary pair IDS 05158+1848, together with HD 242893. However, this latter is at a distance of about $35''$ from SAO 94488 and was not included in the LO field of view. We find a close companion to SAO 94488, with the parameters listed in Table 3. This star is listed as binary also in the Hipparcos catalogue, with separation and PA of $0\farcs130$ and $57°$.

Our result for SAO 94488 is not consistent with that of Hipparcos, unless a significant orbital motion is present. However, two points should be mentioned. Firstly, the Hipparcos catalogue does not indicate changes of the above listed parameters during its observations between 1990 and 1993, while a substantial difference exists with our measurement at epoch 2000.1. Secondly, the Hipparcos parallax for this star, even accounting for the very large relative error, places it at no less than ≈400 pc. Therefore, it would seem that the minimum orbital period should be of the order of a few hundred years.

Unless a combination of high eccentricity and epoch of periastron is speculated, the two points seem difficult to reconcile and we consider this as an open problem in which further observations would be very needed. We note that if the Hipparcos parallax is assumed, the primary must be at least a giant. In this hypothesis, the combination of our result for the brightness ratio and that of Hipparcos, leads to an estimate of G0III and A7V for the primary and secondary respectively. This would also rule out the physical association with HD 242893.

2.8. *SAO 77810*

We detect SAO 77810 to be a triple star, with the parameters listed in Table 3. The data and best fit are shown in Fig. 1. No companions were known before our observation. The spectral type of the companions can be constrained to be around early K or middle M, depending on whether the primary is a giant or a dwarf star. Considering the absence of a Hipparcos determination of the parallax, the first hypothesis seems more likely. This source was observed earlier in the visible by LO, but the companions were not detected (Africano et al. 1976).

2.9. *Remaining stars*

There is no literature available for IRAS 18154-1900, SAO 98345, SAO 93947, SAO 97319, SAO 97437, DO 11742, SAO 78027. For SAO 79799 McAlister et al. 1993 reported no detection of binarity by speckle observations. Our LO light curves reveal a companion around these sources for the first time, with the parameters listed in Table 3. IRAS 18154-1900 is an infrared source with no optical counterparts. In particular, an examination of an ESO survey plate shows that it is barely visible with an upper limit of R$\gtrsim$20. The fluxes at 12 and 25 μm, together with our estimate of the K magnitude, indicate that this is indeed a stellar source. Given the galactic coordinates, a significant amount of interstellar extinction is quite likely, but in view of the considerations above it seems natural to assume that circumstellar dust also plays an important role.

3. Stars with negative binary detection

In this paper, this section is limited to one star only, namely SAO 94961. This source is a suspected LO binary with $\rho_{\rm P}$=20 mas along PA=219° and ΔB=1 mag (Edwards et al. 1980). Speckle observations in the visible have not resolved this source (Mason 1996). We also fail to detect the companion from our LO observations. Our lightcurve has a SNR of 8.6, and the predicted PA was 69°.

4. Statistical considerations in connection with long-baseline interferometry

The field of binary stars is one of the oldest in astronomy, and yet one in which observational work is very active and in continuous evolution. In particular, we should like to mention that the introduction of new large interferometric facilities such as the Keck and the VLTI will soon impact this field of infrared binary studies enormously, by combining large mirrors with hectometric baselines. This will provide angular resolutions at the milliarcsecond level, on sources with magnitudes of order K $\approx$8–12 in the near infrared, or even fainter with suitable off-axis fringe tracking.

It is worthy to note that lunar occultations are the only technique which has already probed this range of resolution and sensitivity, in spite of important limitations in the sky coverage and in the ability to choose its targets and times of observation. The series of papers to which this article belongs represents a homogenous database of binary stars observations in the near-IR. Although it does not possess the richness of other dedicated LO programs such as the series by Evans and his group (Evans et al. 1986, and references therein), it has the advantage of being specific for the near-IR range, where Keck and the VLTI will be most sensitive for this kind of studies. It is then perhaps useful, to draw some rough statistics on the sample of binary stars observed so far.

A summary of the results published in this series of papers is listed in Table 4. The symbols under the field labeled detections indicate new, known, missed and wide binaries, respectively. We have reported on 86 LO events of 77 binary stars: in 45 cases one or more previously unknown components were detected; 18 were previously known and our measurement served as a confirmation, or provided new data at a different wavelength; 13 were previously known binaries, which we did not detect for different reasons; and finally 3 were wide (i.e., above 1″) pairs. The grouping according to the degree of multiplicity of the systems is also shown in Table 4, and it can be noted that within the limitations of the small sample it follows the expected hierarchical behaviour.

Table 4. Statistics of our sample of LO binaries

Paper	LO / stars	detections				multiplicity		
		n.	k.	m.	w.	2	3	≥4
I	10 / 9	7	3	0	0	8	0	1
II	16 / 15	8	2	5	0	9	1	0
III	20 / 16	9	4	3	0	14	2	0
IV	21 / 20	7	7	4	2	14	2	0
V	19 / 17	14	2	1	1	14	1	2
Total	86 / 77	45	18	13	3	59	6	3

In the same period of time covered by this series of papers, we have observed a total of 454 LO of field stars. With this term, we mean stars which were not included in other LO programs such as YSO's and angular diameter stars. For the largest part, these are SAO stars without a bright near-IR flux (i.e., K$\gtrsim$ 3 mag). A significant fraction however is represented also by IRAS sources with no optical counterpart, or a faint one (i.e., not SAO stars).

All except one of the stars used to build the statistics of Table 4 fall within our definition of field stars. Additionally, we exclude the 3 wide binaries. The result is that our LO program has yielded a rate of (44+18)/454 $\approx$14% of field stars, which have turned out to be binary or multiple at the resolution and sensitivity provided by the technique. We note that this conclusion is very similar to the early estimates which we had listed in Table 5 of Paper III. The present value is slightly higher, which is consistent with the fact that the earlier estimates presented in Paper III had not been corrected for objects which did not fall under the present definition of field star.

Of course, this is a biased result, since the sources have a wide distribution of parameters, as shown in Figs. 2-3. Moreover, the LO technique has detection limits which depend significantly on the specific conditions of observation, as discussed in Richichi et al. (1996b). Nevertheless, we note that both the sensitivity and the resolution limits of our sample are comparable with those foreseen for the Keck and the VLTI. In particular, our measurements by LO have detection characteristics which can be very well compared to what is expected for the VLTI in its VISA mode (i.e, 1.8 m apertures with baselines up to 200 m).

For a quantitative estimate, we have used the Catscan facility of IPAC to count the infrared sources measured by the 2MASS (Two Micron All Sky Survey) having K $\leq$8.5 and visible from Paranal. Neglecting corrections for the present incompleteness of the survey (between 5 and 10%), and for sources which would not fulfill our above definition of field stars, a total of $\approx 7.0\times10^5$ sources can be foreseen to be studied in principle with the VLTI/VISA array. Our above conclusions would then indicate that there are potentially about 10^5 binary stars that can be discovered by the VLTI in survey mode. This number is so large that it exceeds the practical observing capability, and

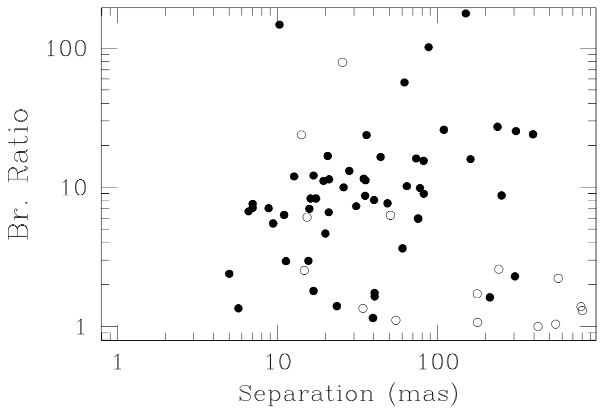

Fig. 2. The binaries of Table 5, shown in a projected separation–brightness ratio (at K) diagram. Repeated observations of the same system are shown independently. Multiple stars are reported as several pairs, each of the primary with a different companion. The filled circles mark the systems discovered by us, the open circles those which were known prior to our observation.

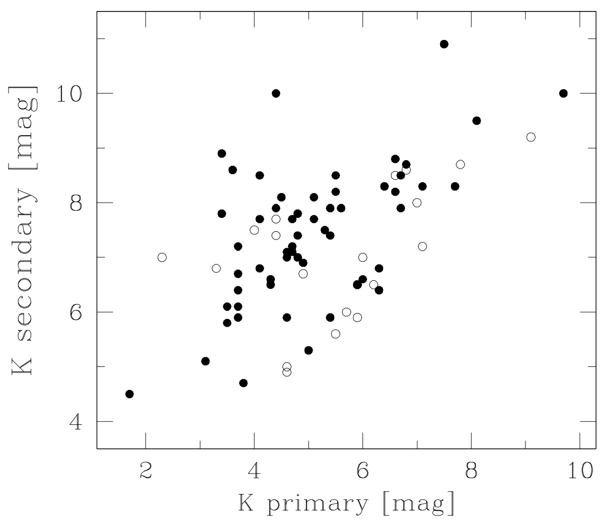

Fig. 3. The binaries of Table 5, shown in a primary-secondary K-brightness diagram. The same rules as for Fig. 2 apply.

probably also the observers' ability to analyze and interpret that data. Selection criteria for an optimized use are thus desirable.

5. Conclusions

We have reported on lunar occultation observations in the near-infrared of seventeen sources. The results include 13 binary stars, 1 triple, and 2 systems with higher multiplicity (among these latter, ζ Cnc has a special relevance and will be discussed in detail in a separate paper). One star was previously detected to be a binary, but we could not detect the companion. We note that in 14 cases, we detected one or more new components to binary or multiple systems. The projected angular separations in our results range from $0\farcs005$ to $0\farcs160$, the K-band magnitudes of the companions are as faint as K≈8.5.

Therefore, this kind of measurements are ideally suited to be followed up with the large interferometric facilities which are soon to become avalable, such as the Keck and the VLTI. We have examined the lunar occultation binary results for field stars which have been published in this series of papers. We find that with this kind of angular resolution and limiting magnitude, one can expect to find about 14% of field stars to be binary or multiple. Considering the large number of sources available for studies by a large interferometer, we estimate that $\approx 10^5$ binary sources could be detected in survey mode.

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