

FINAL BINARY STAR RESULTS FROM THE ESO VLT LUNAR OCCULTATIONS PROGRAM*

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ABSTRACT

We report on 13 subarcsecond binaries, detected by means of lunar occultations in the near-infrared at the ESO Very Large Telescope (VLT). They are all first-time detections except for the visual binary HD 158122, which we resolved for the first time in the near-infrared. The primaries have magnitudes in the range $K = 4.5\text{--}10.0$, and companions in the range $K = 6.8\text{--}11.1$. The magnitude differences have a median value of 2.4, with the largest being 4.6. The projected separations are in the range of 4–168 mas, with a median of 13 mas. We discuss and compare our results with the available literature. With this paper, we conclude the mining for binary star detections in the 1226 occultations recorded at the VLT with the ISAAC instrument. We expect that the majority of these binaries may be unresolvable by adaptive optics on current telescopes, and they might be challenging for long-baseline interferometry. However, they constitute an interesting sample for future larger telescopes and for astrometric missions such as GAIA.

Key words: binaries: close – occultations – stars: fundamental parameters – techniques: high angular resolution

Online-only material: color figures

1. INTRODUCTION

We continue our series of results from a routine program of lunar occultations (LOs) observed in the near-infrared with the ESO Very Large Telescope (VLT). The observational data, the analysis, and the type of results—namely, binaries with small projected separations and largely consisting of first-time detections—closely follow those presented in Richichi et al. (2013, hereafter R13) and other papers referenced therein. Accordingly, we keep the introduction and the data analysis to a minimum.

In Section 2, we briefly summarize the observations and the data analysis. In Section 3, we comment on the list of sources and we discuss the individual results when possible in the context of the available literature.

With this batch of results, we have now exhausted the LO observations of the VLT using the ISAAC instrument for data concerning the detection of binary stars. In Section 4 we provide some statistical conclusions.

2. OBSERVATIONS AND DATA ANALYSIS

The observations were carried out in 2012 from April through October, and cover ESO Periods 89 and 90. We used the 8.2 m UT3 Melipal telescope of the VLT and the ISAAC instrument (Moorwood et al. 1999) operated in burst mode. In each period, 15 hours of telescope time were allocated, and were used to observe 161 and 130 occultation events, respectively, including pointing, acquisition, and other overheads. In fact, the P90 time allocation had started already before the end of P89, and the observations were concluded early in the period given the pending decommissioning of ISAAC.

All observations were carried out in service mode, based on a long list of potentially observable events from which the actual targets were later chosen by the observatory staff, depending on the availability of suitable time slots. As a result, the sources were inherently selected at random. As expected, the majority were found to be unresolved. In a previous paper (Richichi et al. 2012), we listed those observed until 2012 June. A few sources were found to be resolved or extended, and will be the subject of future publications. Here, we deal with those found to be binaries. They are listed in Table 1, with the same format used in R13. They are denoted by a sequential number for ease of reference across this paper, and by a field “Our ID,” which includes the ESO period and the designation in our database.

Our predictions were generated from the Two Micron All Sky Survey (2MASS) Catalog, from which the near-infrared photometry listed in Table 1 is also drawn. We did not attempt to derive proper K -band photometry from our light curves, but we compared our measured counts with those predicted based on the 2MASS magnitude. Cases in which a significant discrepancy was present are noted in Section 3.

Each observation consisted of 7500 frames in a 32×32 pixel ($4''.7 \times 4''.7$) sub-window, with a time sampling of 3.2 ms. This was also the effective integration time. A broadband K_s filter was employed for all events, except in the case of the bright Star 6, for which a narrowband filter centered at $2.07 \mu\text{m}$ was employed to avoid possible nonlinearities. The events were disappearances, with lunar phases ranging from 35% to 97% (median 68%). The airmass ranged from 1.0 to 2.0, while seeing ranged from $0''.6$ to $1''.2$ (median $0''.8$). In any case, the LO light curves are largely insensitive to atmospheric perturbations.

Details on the conversion of the data cubes to light curves and on the data analysis have been given in R13 and references therein. It should be noted that in general we restrict our analysis to $\approx 0''.5$ around the main event. Therefore, any companions with

* Based on observations made with ESO telescopes at Paranal Observatory.

Table 1
List of Detected Binaries

Seq	Our ID	2MASS ID	Simbad ID	Date	UT	<i>B</i>	<i>V</i>	<i>J</i>	<i>H</i>	<i>K</i>	Sp.
1	P89-001	10304197+0354115	BD+04 2345	2012 Apr 4	04:15:03	10.19	9.75	8.77	8.58	8.49	F8
2	P89-040	17121145–2134332	IRAS 17091-2130	2012 Jul 2	05:29:17			7.08	6.03	5.60	
3	P89-042	17123952–2136216	HD 155469	2012 Jul 2	05:45:02	7.40	7.03	6.23	6.07	6.00	F2V
4	P89-055	12460117–0918482	LTT 4882	2012 Jul 25	00:47:16	8.74	8.05	6.88	6.58	6.51	G4
5	P89-056	12480144–0908398	HD 111241	2012 Jul 25	01:22:37	9.23	8.85	8.04	7.84	7.76	F0
6	P89-102	17262278–2122494	TYC 6246-232-1	2012 Aug 26	00:55:45	12.18	10.16	5.76	4.82	4.46	
7	P89-114	17281619–2057493	HD 158122	2012 Aug 26	02:17:30	8.37	7.94	7.01	6.81	6.74	F5V
8	P89-122	17301612–2118427		2012 Aug 26	03:21:33			8.44	7.14	6.44	
9	P90-022	19145561–1810419	IRAS 19119-1816	2012 Sep 24	03:16:13			6.12	5.23	4.89	
10	P90-081	20470928–1223274	HD 197928	2012 Oct 23	00:19:32	10.85	9.96	8.10	7.64	7.57	K3V
11	P90-104	21412408–0744005	LTT 8643	2012 Oct 24	02:23:20		12.20	9.39	8.75	8.57	K5
12	P90-108	21423384–0745278	HD 206492	2012 Oct 24	03:02:12	10.00	9.12	7.43	6.97	6.84	G5
13	P90-123	23184633+0128348	StKM 1-2114	2012 Oct 26	02:43:17		12.50	9.94	9.41	9.25	K5

projected separations larger than this would not appear among our results.

3. RESULTS

Table 2 lists our results, with the same format as R13. The same sequential number used in Table 1 is included, along with the 2MASS identification. The next columns are: the observed rate of the event, its deviation from the predicted value, the local limb slope ψ , and the observed position angle P.A. and contact angle C.A. We then list the signal-to-noise ratio (S/N) of the fit to the light curve, the separation and brightness ratio with their errors, and the two individual magnitudes based on the total 2MASS magnitude.

Due to the selection criteria of our service mode targets, as already discussed in R13, some of the stars in our list are in the direction of the Galactic Bulge. They have generally very red colors, which, however, when plotted in a color–color diagram, appear consistent with the significant amounts of interstellar extinction expected in the Bulge. As a result, a few of our sources have no optical counterparts and no spectral information. In the rest of this section we discuss the individual cases, following sequential numbering.

Star 1. This is BD+04 2345 = SAO 118343. In spite of the relatively large projected separation and small brightness ratio that we detect, it does not appear to have been recorded as a binary before. It was included in Tycho-2 (Høg et al. 2000) and TDSC (Fabricius et al. 2002). The TDSC separation detection limit is $0''.3$, and we conclude that the actual separation is also below this value. The alternative hypothesis, that the companion is considerably redder (i.e., fainter in the visual) than the primary, seems less probable in view of the lack of infrared excess in the colors listed in Table 1.

Star 2. This is an infrared source detected by IRAS (17091-2130) and AKARI. The source is in the bulge. Its near-IR colors appear be consistent with $\lesssim 5$ mag of visual extinction but no visual counterpart is present, possibly pointing to local (e.g., circumstellar) extinction. The 2MASS and DENIS measurements are significantly different, $J = 7.083 \pm 0.013$ and $K_s = 5.601 \pm 0.022$ versus $J = 6.573 \pm 0.05$ and $K_s = 4.705 \pm 0.06$, suggesting a variable nature of the source. Our LO counts are consistent with the 2MASS flux.

Star 3. This star is SAO 185150 = HD 155469 and is listed in multiple visual catalogs, among them HIPPARCOS (HIP 84198), Tycho-2, and TDSC. However, it was not flagged as double in any of them, possibly because of the close separation between the components. Interestingly, a previous occultation

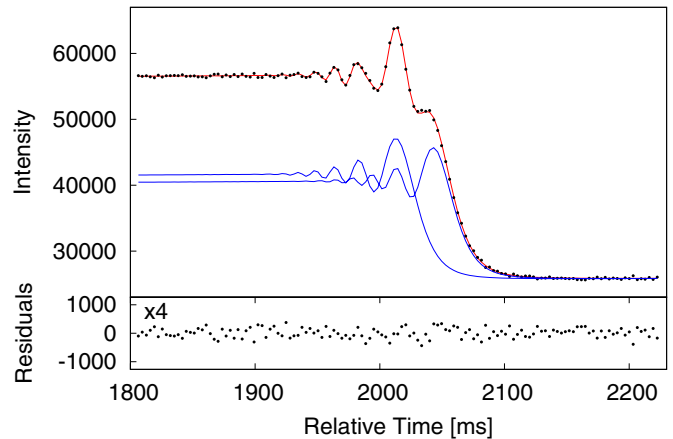


Figure 1. Occultation light curve (dots) and best fit (solid line) for HD 155469, showing its first detection as a binary star. For illustration, the light curves of the two components are also shown. The χ^2_ν of the binary fit is 0.97. The lower panel shows the fit residuals, enlarged for clarity.

(A color version of this figure is available in the online journal.)

recorded on 1982 July 4 was reported by Evans & Edwards (1983), also in this case without detection of binarity. This was a two-channel photoelectric observation in the blue and red, and the authors quote upper limits on the flux difference of a possible companion of about 2.8 mag (our value is <0.1 mag). Their observation and ours were recorded along P.A.'s differing by 58° , and are separated by almost exactly 30 yr; this is significantly longer than the period that we estimate below. SAO 185150 was included in a catalog of empirical angular diameters by Masana et al. (2006) who estimate a value of 0.252 mas. We can only put an upper limit of 2 mas on the angular size of the components (see Richichi et al. 2012), but we note that if they had significantly different colors, a discrepancy would have been noted in the spectral energy distribution (SED), especially in consideration of the high accuracy claimed by the authors (1% in effective temperature).

Contrary to the above observations and estimates, Figure 1 clearly shows the binary nature of SAO 185150. The lack of detection in the Tycho and previous LO data suggests that projection effects should not be very large. For the sake of discussion, we assume the average deprojection factor of $\pi/2$, i.e., a true separation of ≈ 20 mas. SAO 185150 is classified as an F5 dwarf, and with its apparent brightness Hipparcos consistently measured a parallax corresponding to 86 pc (van Leeuwen 2007), which would imply an actual separation of

Table 2
Parameters of Detected Binaries

Seq	2MASS	V (m ms ⁻¹)	V / V ₁ -1	ψ (°)	P.A. (°)	C.A. (°)	S/N	Sep. (mas)	Br. Ratio	K ₁	K ₂
1	10304197+0354115	0.4823	-9.3%	-5	252	39	18.6	168.3 ± 1.6	2.46 ± 0.01	8.86	9.84
2	17121145-2134332	0.7242	-1.7%	-5	86	3	212.9	5.1 ± 0.2	21.8 ± 0.2	5.65	9.00
3	17123952-2136216	0.7492	3.3%	7	287	25	175.7	13.0 ± 0.3	1.0729 ± 0.0009	6.72	6.79
4	12460117-0918482	0.4382	22.1%	7	2	70	62.4	8.3 ± 0.4	17.7 ± 0.2	6.57	9.69
5	12480144-0908398	0.7158	-9.2%	-11	260	-31	19.7	5.41 ± 0.08	2.90 ± 0.05	8.08	9.24
6	17262278-2122494	0.5457	-0.4%	0	117	33	77.8	8.6 ± 0.4	39.1 ± 0.9	4.49	8.47
7	17281619-2057493	0.4946	-4.5%	3	219	-47	50.9	82.6 ± 0.8	1.187 ± 0.002	7.40	7.59
8	17301612-2118427	0.3095	-20.6%	-6	134	55	79.0	18.8 ± 0.3	22.0 ± 0.1	6.49	9.84
9	19145561-1810419	0.6740	25.7%	14	313	64	190.5	15.2 ± 0.2	67.0 ± 0.4	4.90	9.47
10	20470928-1223274	0.6285	-2.7%	-6	66	5	72.8	18.0 ± 0.5	10.09 ± 0.05	7.67	10.18
11	21412408-0744005	0.6831	-1.6%	-4	223	-15	26.7	14.3 ± 0.8	8.8 ± 0.1	8.69	11.05
12	21423384-0745278	0.7241	6.6%	10	95	35	77.4	4.20 ± 0.03	1.54 ± 0.01	7.38	7.85
13	23184633+0128348	0.3660	-11.4%	-6	182	-55	11.3	6.4 ± 2.7	1.05 ± 0.02	9.97	10.03

≈ 2 AU. We find a flux ratio close to unity, and assuming a total mass of $\approx 2 M_{\odot}$ and a circular orbit, the period should be of the order of very few years. SAO 185150 appears to be an ideal candidate for an orbital solution when observed by adaptive optics in short wavelengths, with the potential to lead to accurate dynamical masses.

Star 4. This is BD-08 3423 = SAO 138958, a G4 dwarf. It is listed in *HIPPARCOS*, *Tycho-2*, and TDSC without mention of binarity. It is a high proper motion star (LTT 4882), with $\mu(\text{R.A.}) = 311.6 \pm 0.7$ and $\mu(\text{decl.}) = -219.2 \pm 0.5$ mas yr⁻¹, and with a parallax that places it at about 50 pc (van Leeuwen 2007). It was also included in the work by Masana et al. (2006), mentioned for star 3. This system appears to be a good candidate for a rapid orbital determination; a rough estimate based on $\approx 1 M_{\odot}$ and a (deprojected) ≈ 0.7 AU separation point to a period of less than one year.

Star 5. This is HD 111241 = SAO 138971. Similar to the previous stars, it is listed in *Tycho-2* and TDSC but without binarity flags, most likely due to the very close separation between the components. We note that the counts from our LO curve are consistent with a flux almost double that of the 2MASS K_s magnitude.

Star 6. This is an infrared source measured by *AKARI* and *IRAS*. It is the brightest source in our list with $K_s = 4.5$ mag, and in fact we observed it with a narrowband filter to avoid possible nonlinearities. It shows very red colors, which are, however, consistent with its location in the Galactic Bulge.

Star 7. This is HD 158122, a well known visual binary (ADS 10561 AB; Aitken & Doolittle 1932). Its orbit was derived for the first time by Baize (1950), which gave a period of 36.7 yr and a spectral type of the primary of F8. This system has been extensively observed by means of speckle interferometry (see Hartkopf et al. 2000, and references therein). Additional measurements were published by Mason et al. (2009) and Tokovinin et al. (2010). The Sixth Catalog of Orbits of Visual Binary Stars (Hartkopf & Mason 2009) reports an orbital solution that is graded as good, with a period of 45 yr. Using these elements Cvetkovic & Ninkovic (2010) determined the dynamical masses as $1.24 M_{\odot}$ and $1.21 M_{\odot}$ for the primary and secondary, respectively, with a spectral type of F6 for both stars.

Our light curve and best fit are shown in Figure 2. Using the same orbital elements mentioned above, we estimate that at the date of the occultation, the P.A. was 196° and the separation $0''.105$. Our measured projected separation appears smaller than the expected one (83 instead of 97 mas), but approximately in agreement given possible uncertainties in the orbital elements

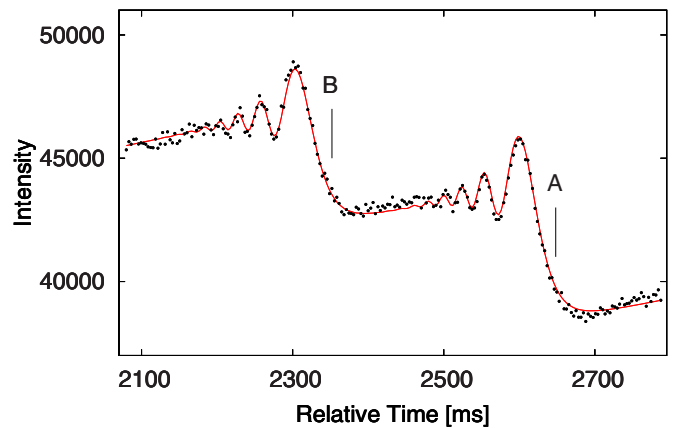


Figure 2. Occultation light curve (dots) and best fit (solid line) for HD 158122, the only previously known binary star in our list. The times of geometrical occultation of the two components are marked.

(A color version of this figure is available in the online journal.)

and also in our predicted P.A. Our LO derived brightness ratio in the K band is an additional first-time constraint to the luminosity of the two components.

Star 8. 17301612-2118427 does not have a known optical counterpart. It is the second reddest object in our list, with $J - K = 2.0$ mag. We note that our counts show only about half of the flux measured by 2MASS, pointing to variability.

Star 9. 19145561-1810419 is an infrared source detected by *IRAS*, *AKARI*, and *WISE*. It was listed in *Tycho-2* with no report for binarity, and the measured proper motions are statistically undistinguishable from zero. One 2MASS and two DENIS measurements are available in J and K_s , but they differ significantly (in the range 5.4–6.1 mag and 4.0–4.9 mag in the two bands, respectively, with small errors), suggesting a variable nature of the source. Also, Pojmanski et al. (2005) report a 0.15 mag V -band amplitude. Ammons et al. (2006) determined an effective temperature $T_{\text{eff}} = 5958^{+751}_{-772}$; however, Ofek (2008) estimated a cooler spectral class of M5 III; Pickles & Depagne (2010) also derived a spectral type of M5 III and a distance of ~ 1.6 kpc. The variability, together with the mid-IR detections, indicate that this may be an AGB star. Finally, the object was detected by *Galaxy Evolution Explorer* (GALEX).

Star 10. This is HD 197928, a nearby high proper motion dwarf star, listed in FOCAS-S, *HIPPARCOS* (HIP 102569), and *Tycho-2*, but with no mention of possible binarity. The star was also detected by *WISE* and *GALEX*. Objective prism spectra

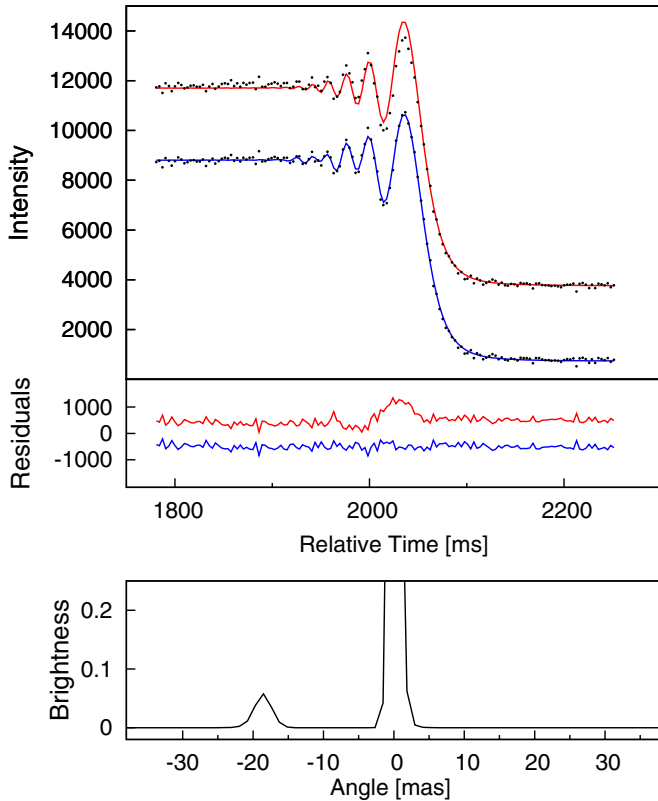


Figure 3. Upper panel: occultation data (dots) for HD 197928, a newly detected binary, with best fits by a single (above) and a binary star (below). The middle panel shows the residuals for the two cases, shifted by ± 500 counts for clarity. The χ^2_n values for the single and binary source fits are 3.42 and 1.06, respectively. The model-independent brightness profile is shown in the bottom panel. The profile of the central star is truncated in this enlarged view.

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yielded a spectral type K2V (Uggen et al. 1972). Ammons et al. (2006) determined an effective temperature $T_{\text{eff}} = 4938^{+74}_{-122}$, metallicity $[\text{Fe}/\text{H}] = -0.12^{+0.32}_{-0.24}$, and a distance $D = 57^{+53}_{-21}$ pc; Ofek (2008) estimated a spectral class K0 III but the luminosity class seems inconsistent with the measured parallax; Pickles & Depagne (2010) derived a spectral type K3 V and a distance $D \sim 42$ pc; Bailer-Jones (2011) estimated somewhat higher effective temperatures, $T_{\text{eff}} = 5879^{+486}_{-505}$ or $T_{\text{eff}} = 5604^{+293}_{-357}$, depending on the adopted models. Interestingly, Ammons et al. (2006) give nearly zero probability for binarity, based on the quality of their SED fit. A model-independent fit to the data (CAL method; Richichi 1989) already revealed the presence of a companion, as shown in the bottom panel of Figure 3. The model-dependent fit confirmed this and in fact convincingly rules out the single star hypothesis.

Star 11. This is a nearby high proper motion star, first identified by Luyten (1957; LTT 8643). In the revised NLTT, Salim & Gould (2003) report $\mu(\text{R.A.}) = 143.4 \pm 5.5$ and $\mu(\text{decl.}) = 203.8 \pm 5.5$ mas yr $^{-1}$. Kuiper classified it as K4/5 V (Bidelman 1985), and Stephenson (1986b) as K5 V. The 2MASS and DENIS magnitudes agree, within the errors. Pickles & Depagne (2010) derived a spectral type of K7 V and a distance of ~ 64 pc. The object was detected by *WISE*, *GALEX*, and the Sloan Digital Sky Survey (SDSS).

Star 12. HD 206492 = SAO 145602 was listed in both FOCAS-T-S (Bystrov et al. 1994) and *Tycho-2* catalogs as an object with small, but measurable proper motion: $\mu(\text{R.A.}) = 11.2 \pm 1.7$ and $\mu(\text{decl.}) = 2.2 \pm 1.9$ mas yr $^{-1}$ (Hog et al.

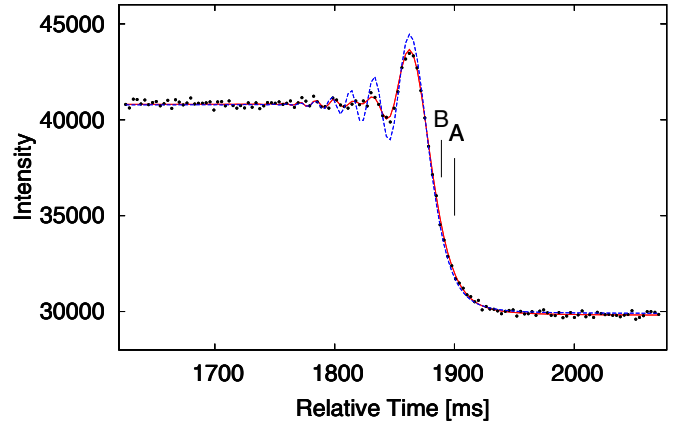


Figure 4. Occultation data (dots) for HD 206492, a newly detected binary with the smallest projected separation among our results. The best fit with a binary source model is shown as a solid line, with segments of a length proportional to the intensity of each component marking their times of geometrical occultation. For comparison, the best fit by an unresolved single source is also shown as a dashed line. The χ^2_n values for the single and the binary source fits are 2.90 and 0.75, respectively.

(A color version of this figure is available in the online journal.)

1998). There is no mention of possible binarity. Objective prism spectra yield a spectral type of G8 III (Houk & Swift 1999). Ammons et al. (2006) determined an effective temperature $T_{\text{eff}} = 4867^{+223}_{-125}$, and a distance $D = 177^{+195}_{-93}$ pc; Ofek (2008) estimated a spectral class of G5 III; Pickles & Depagne (2010) derived a spectral type of K2 V and a distance $D \sim 38$ pc. The object was detected by *WISE*, *GALEX*, and SDSS. Rybka (2007) suggested that the object may be a local Red Clump star, based on its K_s -band reduced proper motion. Our light curve and best fit are shown in Figure 4. Our counts show about 30% flux decrease with respect to 2MASS.

Star 13. This is a nearby K5 dwarf with small proper motion (Stephenson 1986a). The 2MASS and DENIS colors agree within the errors, and our LO counts also agree with the 2MASS magnitude; the source does not seem to exhibit large variability. The object was detected by *WISE*, *GALEX*, and SDSS, and also in some UKIDSS filters.

4. CONCLUSIONS

With the observations reported here, we have exhausted the sample of LOs observed at the VLT with ISAAC, which is about to be decommissioned. A total of 1226 events were recorded over almost exactly seven years (with gaps of up to a year in between). Discarding the negative detections and the grazing events, we could analyze 1161 light curves. The majority of these were found to be unresolved (Richichi et al. 2012), and several showed an extended appearance. Many in this latter class are still awaiting publication. Concerning binary and multiple systems, with the present work we have totaled 97 stars, or a detection rate of $\approx 8\%$ among randomly selected stars. Of these, 90 were first-time detections.

Specifically for this paper, from the first to the last night considered in Table 1, a total of 290 LO light curves were observed; therefore, our binary detection fraction is $\approx 4.5\%$ (13/290), which is less than the value above and also less than the 6.5% rate reported in R13. As already discussed in the latter work, the sky distribution of the sources may indirectly affect their average distance. For an equal distribution of separations, more distant stars will be harder to detect as binaries.

As was the case in R13, half of the binary stars in this paper have flux ratios in the range $2 \leq \Delta K \leq 4.6$ mag. This makes them challenging for long-baseline interferometry. As for the separations, even allowing for a deprojection factor, they are largely inaccessible to current very large telescopes, even with adaptive optics. The follow-up of most of these systems will thus be possible mainly with future extremely large telescopes. Concerning astrometric confirmation and follow-up, the majority of our newly detected systems were beyond the capabilities of *Hipparcos*, but they should constitute a valuable benchmark for the validation and performance assessment of more accurate future observations, such as those made possible by GAIA.

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