A&A 541, A96 (2012)
DOI: 10.1051/0004-6361/201219041

Astronomy & Astrophysics

An investigation of binary stars in the Pleiades with high contrast and spatial resolution★

A. Richichi[1], W. P. Chen[2,3], F. Cusano[4], O. Fors[5,6], M. Moerchen[7,8], and S. Komonjinda[9]

[1] National Astronomical Research Institute of Thailand, 191 Siriphanich Bldg., Huay Kaew Rd., Suthep, Muang, 50200 Chiang Mai, Thailand
e-mail: andrea@narit.or.th
[2] Graduate Institute of Astronomy, National Central University, 300 Jhongda Road, 32001 Jhongli, Taiwan
[3] Department of Physics, National Central University, 300 Jhongda Road, 32001 Jhongli, Taiwan
[4] INAF – Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy
[5] Departament Astronomia i Meteorologia and Institut de Ciències del Cosmos (ICC), Universitat de Barcelona (UB/IEEC), Martí i Franqués 1, 08028 Barcelona, Spain
[6] Observatori Fabra, Camí de l'Observatori s/n, 08035 Barcelona, Spain
[7] European Southern Observatory, Casilla 19001, Santiago 19, Chile
[8] Leiden Observatory, PO Box 9513, 2300 RA Leiden, The Netherlands
[9] Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Muang, 50200 Chiang Mai, Thailand

Received 15 February 2012 / Accepted 15 March 2012

ABSTRACT

Context. It is widely recognized that binarity is a very common feature during star formation; however, different regions and clusters display significantly different binary fractions. This appears to be related to the initial density of the star forming region. The Pleiades cluster has been shown to have a binary fraction similar to that of field stars in the solar neighborhood.
Aims. We have taken advantage of a passage of the Moon over the Pleiades cluster, to investigate at high angular resolution two small but similar and consistent samples of cluster members and field stars.
Methods. We have employed the technique of lunar occultations (LO). Although LO in the Pleiades have been reported several times in the past, we have for the first time employed the superior performance of the VLT, achieving about 1 milliarcsecond (mas) resolution and detecting sources as faint as $K \approx 12$ mag.
Results. We have recorded 17 LO light curves of stars recognized as cluster members, and 17 of field stars. The average magnitude was $K \approx 8.5$ mag and the average limiting resolution $\approx 0\farcs002$, for both samples. We detect 5 binaries among the cluster members, and 2 among the sample of field stars. Three systems are new detections, while two were previously only suspected to be binaries. The projected separations are in the range $0\farcs017$ to $0\farcs642$ and the brightness ratios in the range 1 to 90. One more star is suspected to have a companion.
Conclusions. Although the fraction of binary detections appears higher among the members than among the non-members, the two samples are too small to draw firm conclusions. Our observations show that, in spite of extensive investigations carried out previously in the Pleiades cluster, the binarity census is not yet complete. We have detected significant orbital motion in four binary systems, which stand up as candidates for dynamical mass estimations.

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

1. Introduction

The Pleiades is a relatively young open cluster, with an age (∼100 Myr) that places it at an evolutionary stage intermediate between some of the nearest and best studied very young star-forming regions (SFRs, e.g., Taurus-Auriga and Scorpius-Ophiuchus) and the main sequence. It is also relatively nearby (∼135 pc, although also smaller values have been proposed e.g. by van Leeuwen 2009), placing it on the same spatial scale as the aforementioned SFRs. Its members span a large range of magnitudes and are generally easily identifiable from their colors and proper motions. Naturally, the Pleiades have been intensively studied, among other things, for clues on the binary fraction in clusters and its changes with age and stellar density. One of the most complete studies was reported by Bouvier et al. (1997), who employed near-IR adaptive optics (AO) in observing 144 G and K dwarfs. They concluded that the binary fraction in the Pleiades (≈28% in the considered range of separations) is significantly lower than that observed in some SFRs, such as Taurus, and is consistent with that of other older clusters and with the solar-neighborhood. More recently, studies have concentrated on the binary fraction in the very low mass range (e.g. Lodieu et al. 2007 have reported ≈38%) and on links between 24 μm excess and binarity (Sierchio et al. 2010).

The Pleiades cluster is subject to lunar occultations (LO), although given its large angular size only parts of the cluster are covered at each passage. As an example, its brightest member, the multiple star Alcyone, had occultations visible in principle from many observatories worldwide during 2009 through 2010. The next series will last from 2024 to 2029. We seized the opportunity to observe one such passage in December 2010 from the ESO Very Large Telescope (VLT), where the LO technique has

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

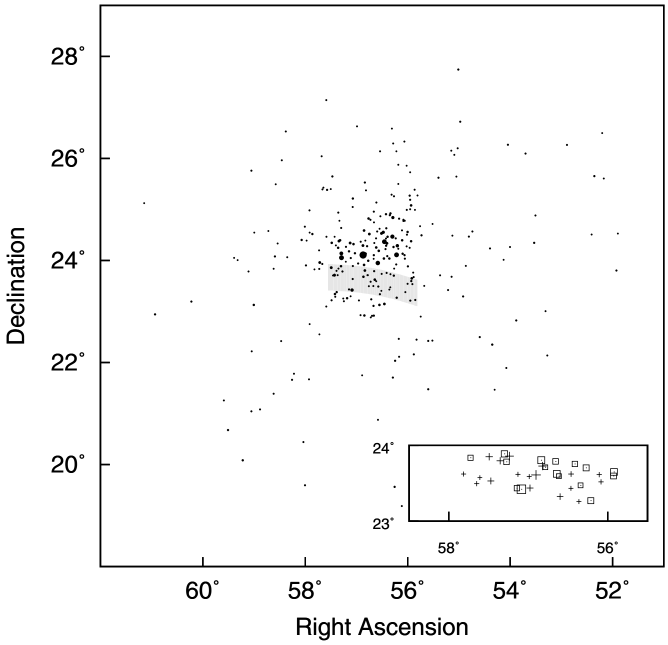

Fig. 1. Spatial distribution of the Pleiades cluster members having $K \leq 10$ mag (from Stauffer et al. 2007), with dots proportional to the K-band brightness. The shaded area shows the path of the Moon during the time covered by our occultation events (only N-S segments through the Moon center are plotted, not its actual circular outline). The inset shows the position of the occulted sources, where cluster members are marked with squares and field stars with crosses.

been well established and widely employed recently (Richichi et al. 2011, and references therein). LO diffraction patterns can be analyzed both with model-dependent and model-independent methods, and are ideally suited to detect binary companions with an angular resolution far exceeding the diffraction limit of a single telescope and a sensitivity significantly better than that currently achieved by long-baseline interferometry. The performance at the VLT has been shown to reach about 1 milliarcsec (mas) and $K \approx 12$ mag.

In this paper we report the results from several tens of occultations of both Pleiades cluster members and field stars.

2. Observations and data analysis

We recorded 34 LOs of stars in the general direction of the Pleiades cluster, using the 8.2-m UT3 Melipal telescope of the VLT and the ISAAC instrument operated in burst mode. The location of the sources is shown in Fig. 1. Each observation consisted of 7500 frames in a 32×32-pixel ($4\farcs7 \times 4\farcs7$) subwindow, with a time sampling of 3.2 ms. This was also the effective integration time. A broad-band K_s filter was employed. The events were disappearances, with a lunar phase of 95%. Airmass ranged from 1.5 to 2.3, while seeing was on average $1\farcs0$. In any case, these parameters do not affect the quality of LO data significantly. The data cubes were converted to light curves using a mask extraction, and these in turn were analyzed using both a model-dependent (Richichi et al. 1996) and a model-independent method (CAL, Richichi 1989). The latter allows us to detect faint binaries or outline complex geometries, while the former is ideally suited to perform detailed least-squares fits. Convergence is driven by changes in normalized χ^2 and this is in turn determined from noise parameters extracted from portions of the light curves before and after the occultations. Details on the instrumentation and the method can be found in Richichi et al. (2011) and references therein. Recently, Richichi & Glindemann (2012) reported on small perturbations occasionally observed in high signal-to-noise ratio (SNR) light curves, resulting from irregularities of the lunar limb. Concerning the data set discussed here, no significant perturbations of the fringe amplitudes were observed, and only one case of variable fringe rate was noted. This occurred for HR 1172: the light curve was satisfactorily analyzed with the method described in the above paper and the source was found to be unresolved.

A list of the observations and of the characteristics of the sources is provided in Table 1. We used the 2MASS Catalogue for our predictions, and further identifications are extracted from the *Simbad* database. In the first column we list the ID number in our general VLT occultation database (P86 being the observing period): this is not intended to assign a new designation, since most sources already have one, but only for quick reference across the paper and for chronological order. We provide the SNR and the detection limit $K_{\rm lim}$ for a hypothetical companion. The noise in our light curves is largely due to detector readout and to photon noise from the lunar background, with stellar photon noise and scintillation being generally less important. As a result, the noise is approximately symmetric around the time of the occultation, and we computed $K_{\rm lim}$ as an average. We point out that in some cases (e.g., when the disappearance of the companion occurs after the disappearance of the primary) it could be possible to detect an hypothetical companion slightly fainter than the reported $K_{\rm lim}$. We analyzed only restricted portions of the light curves around the main disappearance, corresponding to angular extensions of $\approx 0\farcs5$.

3. Results

The observed sources can be divided into two samples of cluster members and non-members, with very similar characteristics. Excluding one grazing event, the two samples include 17 and 16 stars, respectively. The average, median and faintest K magnitudes of the two samples are almost identical at about 8.1, 8.5 and 9.9, respectively. Their distributions in a color-color diagram are indistinguishable, and their spatial locations are overlapping (cf. Fig. 1). Also, the median SNR values from the two samples are similar, 29 and 20 respectively. We conclude that a comparison of the binary frequency in these two small samples is justified.

Seven stars were found to be binary, and we list their characteristics in Table 2. For one additional source, we find that the data could be consistent with binarity, but are not sufficiently conclusive; this is mentioned below but is not listed among our results. The table is ordered by time of occultation, following a format similar to that of our previous papers. We list the observed rate of the event V and its deviation from the predicted value V_t. This difference is converted into the local lunar limb slope ψ, and the correspondingly corrected values of the position angle PA and contact angle CA are also listed (cf. Richichi & Glindemann 2012). The separation is the projected value along the PA direction. The magnitudes are derived from our measured K_s brightness ratios, using the 2MASS K magnitudes as a total value. In the following we provide details on some of the sources in our sample.

P86-38: 03434152+2338568 is HD 23157 and SAO 76103. This star was resolved to be a binary with an LO observation on 11 February 1973 by McGraw et al. (1974), with a magnitude difference of δm = 0.95 (unfiltered), and a projected separation of 23.1 mas along PA = $116\fdg3$. The binarity was not clearly

Table 1. List of occulted sources.

ID	Object	Member[a]	Name	V^b	J	H	K	UT	SNR	$K_{\rm lim}$	Notes
P86-36	03434286+2335412	372	HD 23158	9.58	8.54	8.32	8.23	0:54:10	21.7	11.58	
P86-37	03442046+2331040		Melotte 22 HII 332	12.74	9.94	9.26	9.09	1:01:43	11.5	11.74	
P86-38	03434152+2338568	370	HD 23157	7.95	7.20	7.07	7.03	1:08:33	41.8	11.08	Binary
P86-39	03442602+2336480			13.20*	10.15	9.33	9.04	1:16:42	15.1	11.99	
P86-40	03445123+2316082	483	HD 23289	9.01	8.18	8.01	7.98	1:24:40	33.5	11.79	
P86-41	03452219+2328182	535	Melotte 22 HII 636	12.48	10.47	9.96	9.85	1:37:42	5.0	11.60	
P86-42	03450528+2342097	504	HD 23326	8.99	8.21	8.04	8.00	1:52:29	30.2	11.70	
P86-43	03455159+2325547		Melotte 22 HII 815	11.94*	10.12	9.76	9.61	1:59:18	7.2	11.75	Binary
P86-44	03455069+2337153		Melotte 22 HII 803	11.97	9.14	8.49	8.33	2:04:37	24.0	11.77	
P86-45	03452741+2315259			12.70*	10.39	9.83	9.66	2:13:03			Grazing[c]
P86-46	03453940+2345154	559	V1041 Tau	12.26	9.77	9.22	9.01	2:20:37	11.6	11.67	Binary
P86-47	03462777+2335337	658	V641 Tau	13.05	10.59	10.01	9.82	2:26:30	4.5	11.45	
P86-48	03463420+2337264	670	HD 23512	8.15	7.24	7.12	7.07	2:32:38	65.0	11.60	
P86-49	03462414+2319243		Melotte 22 HII1021	10.40	7.98	7.48	7.28	2:46:01	53.9	11.61	
P86-50	03463767+2347159	676	HD 282975	10.00	8.93	8.58	8.53	2:57:02	28.7	12.17	
P86-51	03470853+2342389	740	FL Tau	13.51	10.72	10.10	9.90	3:02:21	6.3	11.90	Binary
P86-52	03471715+2343363		HD 23609	6.99	5.96	5.80	5.74	3:09:35	161.5	11.26	
P86-53	03473695+2336329		HD 23654	7.71	5.57	5.02	4.88	3:14:56	306.6	11.10	
P86-54	03472096+2348121	765	HD 23632	7.02	6.85	6.92	6.90	3:23:58	88.8	11.77	
P86-55	03475731+2335154			12.84*	10.39	9.69	9.53	3:29:15	9.4	11.97	
P86-56	03475496+2326139		BD+22 559	10.00	7.62	7.04	6.86	3:38:53	78.5	11.60	Binary?[d]
P86-57	03483139+2337018		Melotte 22 HII1901	12.57	10.33	9.62	9.44	3:53:16	11.8	12.12	
P86-58	03482081+2325165	882	HR1172	5.44	5.50	5.59	5.56	4:03:52	119.3	10.75	
P86-59	03483451+2326053	903	Melotte 22 HII1924	10.70	9.20	8.98	8.87	4:11:34	16.0	11.88	
P86-60	03490610+2346525	947		10.83	9.17	8.72	8.60	4:24:40	23.5	12.03	
P86-61	03485693+2351259		26 Tau	6.49	5.68	5.53	5.48	4:30:51	202.5	11.24	Binary
P86-62	03492513+2347421			11.74*	7.80	6.84	6.56	4:38:06	109.3	11.65	
P86-63	03491219+2353126	957	HD 23863	8.15	7.67	7.60	7.58	4:47:16	38.1	11.53	Binary
P86-64	03495326+2331503		BD+23 566	9.90	7.65	7.05	6.90	4:54:04	73.2	11.56	
P86-65	03495805+2350554	1029	HD 23964	6.74	6.55	6.59	6.51	5:05:32	103.2	11.55	
P86-66	03502643+2334209		Melotte 22 HII 2698	11.38*	10.28	10.00	9.94	5:12:37	1.5	10.37	
P86-67	03503612+2329357			11.49*	10.06	9.50	9.33	5:26:47	7.5	11.52	
P86-68	03505432+2350056	1087	V1176 Tau	11.48	9.68	9.23	9.05	5:36:56	4.5	10.67	Binary
P86-69	03511531+2337184		BD+23 572	10.70	9.74	9.56	9.52	5:40:47	2.6	10.55	

Notes. The V magnitudes are from *Simbad*, and the JHK ones are from 2MASS. UT times of disappearance are for the date of December 19, 2010 (predicted values). [(a)] Index in the catalogue of Pleiades cluster members by Stauffer et al. (2007). Missing entries denote non-members. [(b)] Values with an asterisk are from Zacharias et al. (2005). [(c)] Data recorded but not analyzed. [(d)] Companion brightness close to the detection limit (see text).

Table 2. Detected binaries.

ID	V (m/ms)	V/V_t–1	ψ(°)	PA(°)	CA(°)	*SNR*	Sep. (mas)	Br. ratio	Magnitudes
P86-38	0.3668	27.3%	8	15	−56	41.8	16.80 ± 0.04	1.378 ± 0.003	K_1 = 7.62, K_2 = 7.97
P86-43	0.5185	−5.2%	−5	96	22	7.2	176 ± 1	1.652 ± 0.009	K_1 = 10.12, K_2 = 10.67
P86-46	0.4331	18.3%	8	30	−45	12.7	473.9 ± 0.8	4.42 ± 0.02	K_1 = 9.23, K_2 = 10.84
P86-51	0.5910	5.3%	11	67	−11	6.3	641.7 ± 0.3	1.352 ± 0.009	K_1 = 10.50, K_2 = 10.83
P86-61	0.3730	−9.9%	−5	30	−55	202.5	18.5 ± 0.2	92.4 ± 0.8	K_1 = 5.49, K_2 = 10.40
P86-63	0.2256	−30.8%	−10	15	−70	38.1	22.1 ± 0.8	42.1 ± 0.8	K_1 = 7.60, K_2 = 11.66
P86-68	0.5420	−2.5%	−2	48	−40	4.5	117.9 ± 0.7	1.08 ± 0.01	K_1 = 9.77, K_2 = 9.85

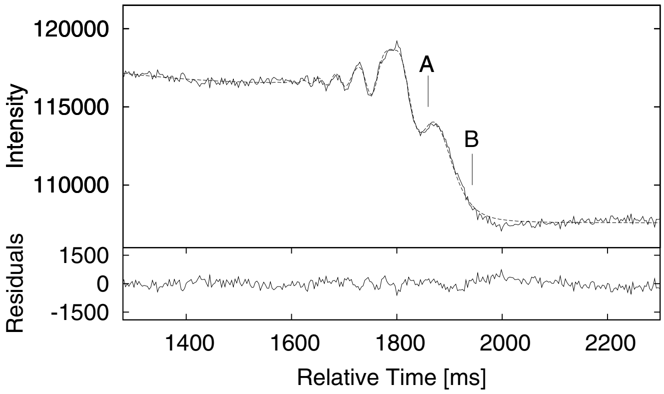

Fig. 2. Occultation data (solid) and best fit (dashed line) for HD 23157, a cluster member. With a brightness ratio close to unity, the two components show well detached disappearances even with a projected separation of 17 mas, three times smaller than the diffraction limit of an 8 m telescope.

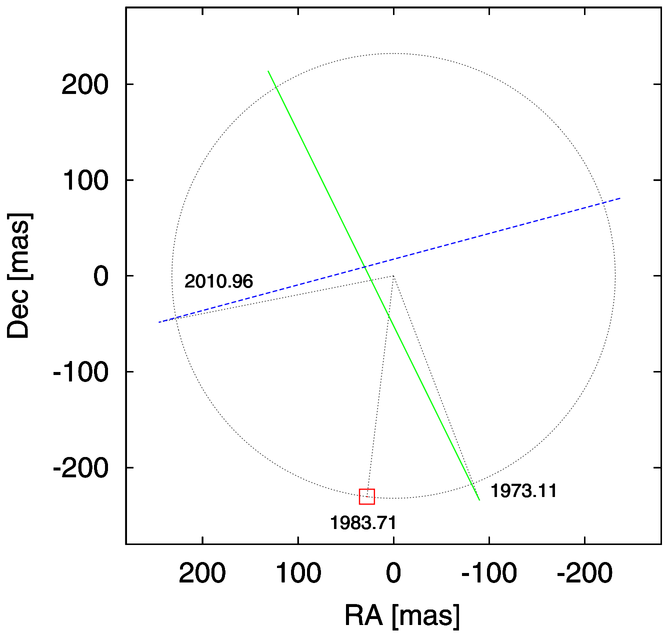

Fig. 3. Available binary measurements for HD 23157. The segments mark the loci consistent with the LO projected separations (solid: McGraw et al. 1974; dashed: present work). The square marks the speckle position by McAlister et al. (1987), with size not related to the error. The dotted circular orbit and orbital segments are shown for comparison only, see text.

detected though in the same 1973 event at a different site with the predicted PA of 21°.2 (Eitter & Beavers 1977). Interestingly, the system was reported to be resolved once by CCD speckle observations with a separation of 0′′.232 along PA = 173°.1 (McAlister et al. 1987). The date was 1983.713 but the magnitude difference remained unreported. However, the object was unresolved in many subsequent attempts by speckle (Mason 1996; Balega et al. 1999). Our light curve clearly reveals the companion (see Fig. 2) and is roughly consistent in magnitude difference with the estimate of McGraw et al. (1974), pointing to roughly similar colors for the two components. However, the three quoted measurements cannot be reconciled in terms of separation and position angle. Since they span almost 38 years, this is to be expected and shows clear evidence of orbital motion, as illustrated in Fig. 3. It can be noted that at a first approximation a circular orbit would be consistent with the observations, with relative motions that are roughly proportional to the 10.6 y and 27.3 y between the measurements. A one-solar mass binary at 130 pc with 0′′.232 separation would have $P \approx 165$ y, also roughly consistent with the tentative circular orbit. SAO 76103 is a relatively easy target for measurements by AO with large telescopes and interferometry, and given its membership in the Pleiades cluster, its monitoring should lead to a complete orbit, possibly quite different from the simple circular approximation shown here, and dynamical mass estimates. A few other systems in our sample also show possible orbital motion, but they have only one previous determination each and cannot be discussed quantitatively at this point.

P86-43: 03455159+2325547 is Mel 22 HII 815. This is a field star, likely in the background, judging by its brightness. Its proper motion (Wang et al. 1996) also suggests non-membership. We resolved this star into a pair with comparable brightnesses. An examination of available images excludes projection effects from nearby stars.

P86-46: 03453940+2345154 is a member of the Pleiades also identified as Melotte 22 HII 738 (Hertzsprung 1947). Breger (1984) classified it as a G9V star with an $E(B-V)$ = 0.39 mag. HII 738 is also V1041 Tau, a flare star first observed by Chavushian & Broutian (1990). An X-ray emission of $6.5 \pm 2.0 \times 10^{29}$ erg s^{-1} was detected by Micela et al. (1985), and a rotational velocity of $v \sin i$ = 50 km s^{-1} was measured by Soderblom et al. (1993). HII 738 was first identified as a photometric binary by Stauffer (1984) using the photometric difference to the main sequence in the $[V]$–$[V-I]$ diagram. An AO survey performed by Bouvier et al. (1997) detected a companion at 0′′.5 along PA = 157°.3. The two components had K = 9.00 and 11.18 mag, respectively. The authors found that the primary HII 738A appears to be brighter by about 0.8 mag in the K band with respect to the Pleiades zero age main sequence and may be itself a photometric binary, but we could not resolve it in our light curve. We make the reasonable assumption that the companion previously measured by AO is the same one detected by us. However, the separation and position angle of the AO and LO measurements are not consistent with each other. Assuming solar masses, a circular orbit and an approximate distance of 130 pc, the AO-measured separation would imply a period of ≈500 years. The AO and LO measurements were separated by just 14.2 years, pointing possibly to a very inclined and/or non-circular orbit. We also note slight but possibly significant changes in the brightness, both absolute and relative, of the two components, pointing to a fading of the primary and a brightening of the secondary.

P86-47: 03462777+2335337 is V641 Tau, listed as a cluster member star by Breger (1996), who gave also a spectral type of K0. Coronal X-ray emission was detected with the *ROSAT* satellite (Hempelmann et al. 1995). This star was first recognized as a flare star by Pigatto & Rosino (1973). Eggen & Iben (1988) listed this star as a possible binary system based on photometric observations. Our light curve does not reveal companions brighter than $K \approx 11.5$ mag within ≈0.″5 from this star.

P86-48: 03463420+2337264 is HD 23512, a cluster member (Breger 1996). Abt et al. (1965) reported a spectral type of A0V for this star. The same authors ruled out the possibility that this star is a binary system by using radial velocity measurements. Moreover, photometric time-series observations showed that HD 23512 is constant at the level of 0.001 V-mag (Breger et al. 1972). A lunar occultation event was observed by Eitter & Beavers (1977), who did not find evidence of a companion star. Another lunar occultation event led to the same conclusion (Frueh et al. 1988). Our light curve confirms and strengthens the single nature of this star.

P86-50: 03463767+2347159 is HD 282975, a G6V-type cluster member and a known double-lined spectroscopic binary. The system orbital elements were calculated by Halbwachs et al. (2003) as $P = 30\overset{\mathrm{d}}{.}2$, $e = 0.33$, $K_1 = 15.2$ km s^{-1}, and $q = 0.53$. Konacki et al. (2009) unsuccessfully studied this star for planetary signatures by means of high accurate radial velocities, and provided a 26-day period estimate. Using the above orbital elements we derive $a \sin\ i \approx 0.1$ AU, or 0.8 mas. Barring extreme combinations of inclination and position angle, our negative detection of the secondary component is justified.

P86-51: 03470853+2342389 is FL Tau, a K5V cluster member. Membership is indirectly confirmed also by its marked flare activity (Haro & Chavira 1966; McCarthy & Treanor 1968), which has been further studied with *ROSAT* (Stauffer et al. 1994; Micela et al. 1999). No previous reference shows evidence of binarity, and the source was not included in the AO survey by Bouvier et al. (1997). Our observation resolved this star as a binary with a relatively wide projected separation of 0.″642 and a flux ratio of 1.35. We note that the source does not show color anomalies in its 2MASS photometry with respect to the standard dwarf locus, but its observed $V - K$ color of 3.61 mag is significantly redder than the intrinsic $(V - K)_0 = 2.85$ mag for a K5 dwarf. A visual inspection of Pan-STARRS images confirms a companion ∼0.″6 away at PA ∼ 60°. The companion is more prominent in the y band (central wavelength near 1 μm) than in the g' band, so it is redder than the primary. The question of which of the components is associated with the aforementioned activity and X-ray emission remains open.

P86-52: 03471715+2343363 is HD 23609, a bright F5 background star. Robinson et al. (2007) measured this metal-rich source as a potential planet-search target. We obtained a high-quality light curve that does not indicate companions. This is consistent with conclusions by Cernis (1987) based on photometry, and by Eitter & Beavers (1977) by means of a previous LO.

P86-53: The case of 03473695+2336329, a bright K0 background star HD 23654, is very similar to the previous one. Also for this star, our high-quality light curve does not reveal companions, in line with results of previous LO observations by Eitter & Beavers (1977) and Frueh et al. (1988).

P86-54: 03472096+2348121 is HD 23632, a A1V cluster member. No binarity was reported by Abt et al. (1965) in their spectroscopic binary survey. Further negative binarity detections were reported in the following works: LO observation by McGraw et al. (1974), *HIPPARCOS* and the post-mission compilation of the Tycho Double Star Catalogue (Fabricius et al. 2002), and deep ICCD observations by Mason et al. (1993). We note also that HD 23632 was employed by Eisner et al. (2010, 2009) as calibrator for the Keck Interferometer, attaining a spatial resolution of ≈1 mas. Our light curve is consistent with no companions brighter than $K \approx 12$ mag.

P86-56: 03475496+2326139 is BD+22 559, a bright G8 background star. It corresponds to TYC 1800-1783-1, which was not resolved as a binary by the post-mission compilation of the Tycho Double Star Catalogue (Fabricius et al. 2002). This source was among those with X-ray flares listed by Andrews (2000) and it was detected by *MSX* (Kraemer et al. 2003), in both cases without mention of binarity. Our light curve is consistent with the presence of a faint companion ($\Delta K = 4.7$ mag) with 45 mas separation along PA = 143°. Such a model produces a marginal improvement in the fit (6% decrease in χ^2). This detection, however, is at the noise limit, and we do not include it in our count of binary results.

P86-59: 03483451+2326053 is Melotte 22 HII 1924. Sierchio et al. (2010) detected excess emission associated with this star at 24 μm with *Spitzer* photometric observations, 4% above the estimated photospheric level. The source was determined to be a potential variable star in optical bandpasses (*VLBUW*) by van Leeuwen et al. (1986). A positive X-ray detection of the source was made with the Einstein Observatory (Caillault & Helfand 1985), and this was later confirmed by *ROSAT* observations (Micela et al. 1996). Our light curve does not reveal companions.

P86-60: 03490610+2346525 is V1282 Tau and LH 98 103. This source was first detected as an X-ray emitter by the Einstein Observatory (Caillault & Helfand 1985), and confirmed in further observations with *ROSAT* (Schmitt 1993). This source was found to be a spectroscopic binary by Queloz et al. (1998) with $B - V_0 = 0.742$, $v \sin\ i = 6.9 \pm 3.2$ km s^{-1} (a component), 10.8 ± 2.3 km s^{-1} (b component); this was confirmed by White et al. (2007). The pair was likewise shown to be a periodic variable by Norton et al. (2007), with $P = 0\overset{\mathrm{d}}{.}3082$ and magnitudes of 11.08, 11.05, 12.00 in V, $B1$, and $R1$, respectively. In spite of the lack of explicit estimates of separation and flux ratio, our non-detection of binarity does not raise inconsistencies in view of the small expected angular separation.

P86-61: 03485693+2351259 is 26 Tau and SAO 76225. It is not a Pleiades member. This star was detected at 8.3 μm with the Midcourse Space Experiment *MSX* by Kraemer (2003). McGraw et al. (1974) found by LO that the source was "probably" a binary (uncertainty due to a noisy second fringe), with a projected separation of 0.″0093 along PA = 94.°9, and $\Delta B = 2.78$ mag. This could not be confirmed by McAlister (1978), by Mason (1996) nor by Frueh et al. (1988), the first two using speckle interferometry and the latter LO. Our measurement shows a companion (Fig. 4) that is indeed on the same order of angular separation as the tentative detection by McGraw et al. (1974), after allowing for projection and orbital motion. The magnitude differences, however, seem to indicate a companion bluer than the primary. As this is an F0 star, there is some question about the reliability of the initial flux ratio.

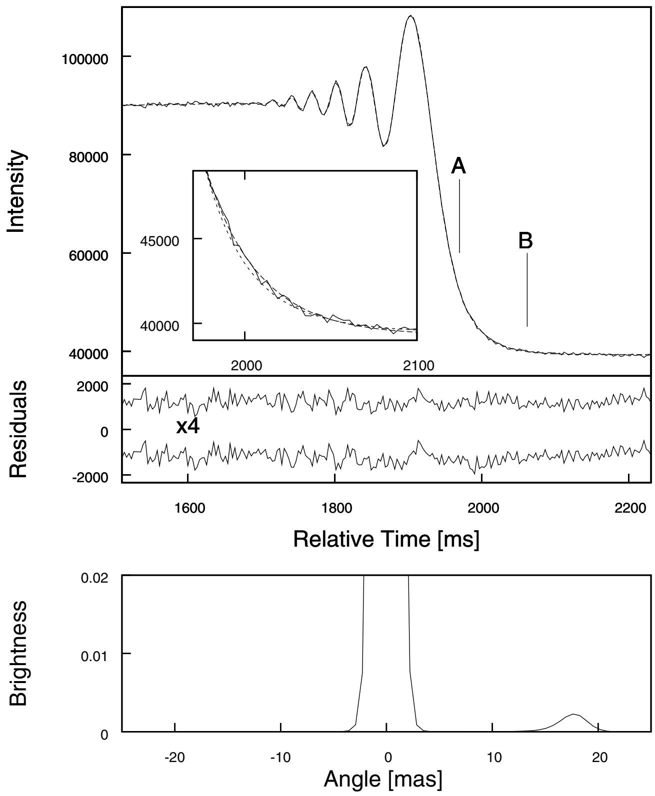

Fig. 4. *Top*: *upper panel*, data (solid) and best fit (dashed line) for 26 Tau, a binary field star with a high brightness ratio approaching 5 mag. The *lower panel* shows, displaced by arbitrary offsets and enlarged for clarity, the residuals of the fits by a point-like (below) and by a binary star model (above). The normalized χ^2 values are 1.44 and 1.09, respectively. The times of the geometrical occultation of two stars are also marked, with their difference corresponding to a separation of 18.5 mas. The inset shows a magnified portion of the data (solid line), and of the fits by a double (upper dashed line) and single (lower dotted line) source. *Bottom*: brightness profile reconstructed by the model-independent CAL method. The brightness scale is not linear.

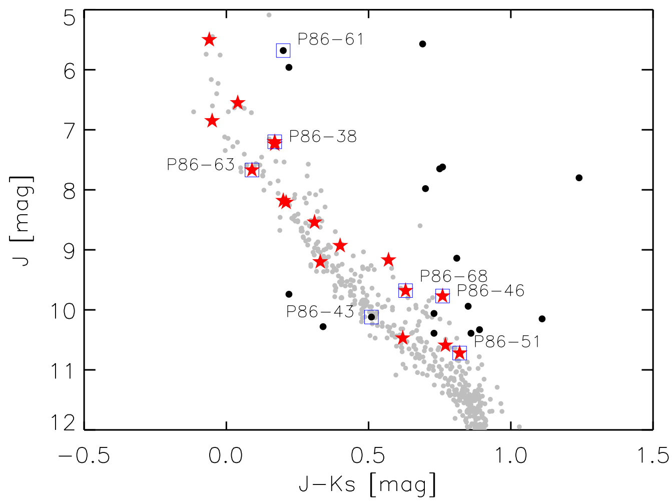

Fig. 5. Color–magnitude diagram for members of the Pleiades cluster (gray dots, from Stauffer et al. 2007). The star and black dot symbols mark the positions of member and non-members, respectively, for which we obtained LO light curves. Those found to be binary are surrounded by a square and identified by their number in Table 2.

P86-63: 03491219+2353126 is HD 23863, a Pleiades member claimed as spectroscopic binary by Liu et al. (1991) from the variation in its radial velocity. We do detect a companion, however it is not clear whether this is related to the RV one given the high brightness ratio and the rather large projected separation from our measurement (see Table 2), and the scarcity of information from the RV analysis. Consequently, we count this as a new detection. The possibility exists that the star is in fact a triple system.

P86-65: 03495805+2350554 is HD 23964, a spectroscopic binary listed by Pourbaix et al. (2004) using the data of Pearce & Hill (1975). The system orbit was assumed to be circular by Lucy & Sweeney (1971). Halbwachs (1981) computed the angular separation of the system as 0.″0016. Our light curve has *SNR* = 103, and we have performed several tests to investigate a possible close binary without positive conclusions. As an illustration, a system with 0.″002 separation and 1:9 flux ratio results in a 17% decrease of the normalized χ^2, which we would very easily detect. The spectroscopic binary is single-lined, possibly indicating a high flux ratio.

P86-68: 03505432+2350056 is V1176 Tau and Melotte 22 HII 2881. This star was included in the AO survey by Bouvier et al. (1997), who reported a possible detection of binarity with equal components separated by 0.″08 along PA = 150°. All these quantities were deemed uncertain, although the star was included in the authors' count of binary fraction in the cluster. Our light curve clearly shows and confirms the binarity, indeed with almost equal brightness components. The angular separation as measured by us, however, is significantly larger, even without considering projection effects, than in Bouvier et al. (1997). As these authors would almost certainly have obtained a better measurement if the separation had been larger, we conclude that the system has undergone a significant orbital motion in the intervening 14.1 years. A 0.″12 binary with one solar mass is expected to have $P \approx 60$ y at the Pleiades' distance. Queloz et al. (1998) reported the star as a suspected long-period double-lined spectroscopic binary. Further high spatial resolution observations could possibly lead to a complete orbital and mass determination for this system.

4. Discussion and conclusions

Overall, we find 3 new binaries (FL Tau and HD 23863, both Pleiades members, and Melotte 22 HII 815, a non-member). We detect and confirm two previously suspected binaries (26 Tau and V1176 Tau, non-member and member respectively), and we provide new additional data on two known binaries (HD 23157 and V1041 Tau). Figure 5 shows a color-magnitude diagram for the Pleiades clusters, overlapped with the sources reported in this paper. It can be seen that most of the members that we found to be binary are located above the main sequence and are indeed systems with comparable flux ratios. The only exception is P86-63, also a member, which lies on the main sequence in agreement with its companion being very faint.

Three of the stars in our sample are known spectroscopic binaries: HD282975, V1282 Tau and HD23964. Additionally, HD23863 and V1176 Tau were claimed as spectroscopic binaries but remain unconfirmed. Based on our achieved angular resolution, we did not expect to detect binarity in any of these systems. We note however that we do detect a companion in HD23863, although it is not clear whether this is related to the changes in radial velocities claimed for this star by Liu et al. (1991). It seems likely that our detection is not related to the possible SB nature of this star, and therefore we count it among our newly detected companions. Two more stars (V1041 Tau-A and V641 Tau) had been previously suspected to be photometric binaries on the basis of their location in the color-magnitude diagram being higher than the Pleiades main sequence, but they were not resolved by us. No other previously known binaries remained undetected in our observations.

Concerning the possibility that some of the binaries are non-physical pairs, until measurements of relative orbital motions are gained we have to rely on statistical considerations. We have counted 366 2MASS stars with $K \leq 12.5$ mag (conservatively fainter than our detection limits in Table 1) in the 0.91 sq. degrees shaded area of Fig. 1. The effective field of view in our data is $\lesssim$1 sq. arcsec, as discussed in Richichi et al. (2011). Therefore the probability of detecting random stars as companions is quite negligible in our small sample.

Excluding the present work, so far 15 different papers have reported LOs of 57 Pleiades members during the passages centered around 1969–1973 and 1987–1988. Of these, at least 18 were found to be binary, although telescope and instrumentation (and hence sensitivity and accuracy) varied significantly between different observers. For the most recent passage around 2010, we are not aware of other observations using large telescopes beyond those described here.

In summary, our samples of member and non-member stars include 5 out of 17 and 2 out of 16 binaries, respectively. We note that both samples include small and large projected separations, as well as high and low brightness ratios. The binary count ($\approx$30%) would appear higher for members of the Pleiades, and intriguingly similar to the result of 28 $\pm$ 4% by Bouvier et al. (1997). In fact, the numbers are too small to warrant any statistical analysis and the significance of the binary fraction is marginal given also that we were not in a position to define our samples on the basis of spectral types and periods, nor did we attempt to correct for incompleteness and other biases. Given the random selection of our sources, our sample is also not homogeneous in terms of range of masses to which we are sensitive. However we note that, using a distance of 130 pc and the relationships provided by Henry & McCarthy (1993), the systems listed in Table 2 have individual masses ranging from $\gtrsim$1 to $\approx$0.5 $M_{\odot}$.

We remark that, by employing the LO technique which provides both high angular resolution and high contrast, we could detect two new binaries in a small sample of Pleiades members already extensively surveyed by a number of other techniques. This clearly shows that the count of binaries in this cluster is not yet conclusive. We also note that our observations have led to the detection of significant orbital motion, on the milliarcsecond/year scale, on four systems which could be selected as candidates for dynamical mass estimations. Further investigations in this cluster would benefit from the highest possible spatial resolution, which is presently warranted by LO and interferometry.

Acknowledgements. O.F. acknowledges financial support from MICINN through a *Juan de la Cierva* fellowship and from *MCYT-SEPCYT Plan Nacional I+D+I AYA#2008-01225*. M.M. acknowledges co-funding under the Marie Curie Actions of the European Commission (FP7-COFUND). We are grateful to the Paranal Observatory staff, and in particular to Dr. V. Ivanov, for the service mode observations of the data reported in this paper under the ESO program 085.D-0689(A). This research made use of the Simbad database, operated at the CDS, Strasbourg, France, and of data products from the Two Micron All Sky Survey (2MASS), which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

References

Abt, H. A., Barnes, R. C., Biggs, E. S., & Osmer, P. S. 1965, ApJ, 142, 1604
Andrews, A. D. 2000, Irish Astron. J, 27, 137
Balega, I. I., Balega, Y. Y., Maksimov, A. F., et al. 1999, A&AS, 140, 287
Bouvier, J., Rigaut, F., & Nadeau, D. 1997, A&A, 323, 139
Breger, M. 1972, ApJ, 176, 367
Breger, M. 1984, A&A, 137, 145
Breger, M. 1986, ApJ, 309, 311
Caillault, J.-P., & Helfand, D. J. 1985, ApJ, 289, 279
Cernis, K. 1987, Ap&SS, 133, 355
Chavushian, H. S., & Broutian, G. H. 1990, IAU Symp., 137, 63
Eggen, O. J., & Iben, I., Jr. 1988, AJ, 96, 635
Eisner, J. A., Graham, J. R., Akeson, R. L., & Najita, J. 2009, ApJ, 692, 309
Eisner, J. A., Monnier, J. D., Woillez, J., et al. 2010, ApJ, 718, 774
Eitter, J. J., & Beavers, W. I. 1977, ApJS, 34, 493
Fabricius, C., Høg, E., Makarov, V. V., et al. 2002, A&A, 384, 180
Frueh, M., McWilliam, A., Evans, D. S., & Coleman, L. A. 1988, AJ, 95, 117
Gorlova, N., Rieke, G. H., Muzerolle, J., et al. 2006, ApJ, 649, 1028
Halbwachs, J. L. 1981, A&AS, 44, 47
Halbwachs, J. L., Mayor, M., Udry, S., & Arenou, F. 2003, A&A, 397, 159
Haro, G., & Chavira, E. 1966, Vistas Astron., 8, 89
Hempelmann, A., Schmitt, J. H. M. M., Schultz, M., Ruediger, G., & Stepien, K. 1995, A&A, 294, 515
Henry, T. J., & McCarthy, D. W., Jr. 1993, AJ, 106, 773
Hertzsprung, E. 1947, Leiden Ann., 19, A1
Konacki, M., Muterspaugh, M. W., Kulkarni, S. R., & Hełminiak, K. G. 2009, ApJ, 704, 513
Kraemer, K. E., Shipman, R. F., Price, S. D., et al. 2003, AJ, 126, 1423
Liu, T., Janes, K. A., & Bania, T. M. 1991, ApJ, 377, 141
Lodieu, N., Dobbie, P. D., Deacon, N. R., et al. 2007, MNRAS, 380, 712
Lucy, L. B., & Sweeney, M. A. 1971, AJ, 76, 544
Mason, B. D. 1996, AJ, 112, 2260
Mason, B. D., Hartkopf, W. I., McAlister, H. A., & Sowell, J. R. 1993, AJ, 106, 637
McAlister, H. A. 1978, PASP, 90, 288
McAlister, H. A., Hartkopf, W. I., Hutter, D. J., & Franz, O. G. 1987, AJ, 93, 688
McCarthy, M. F., & Treanor, P. J. 1968, Ricerche Astron., 7, 367
McGraw, J. T., Dunham, D. W., Evans, D. S., & Moffett, T. J. 1974, AJ, 79, 1299
Micela, G., Sciortino, S., Serio, S., et al. 1985, ApJ, 292, 172
Micela, G., Sciortino, S., Kashyap, V., Harnden, F. R., Jr., & Rosner, R. 1996, ApJS, 102, 75
Micela, G., Sciortino, S., Harnden, F. R., Jr., et al. 1999, A&A, 341, 751
Norton, A. J., Wheatley, P. J., West, R. G., et al. 2007, A&A, 467, 785
Pearce, J. A., & Hill, G. 1975, Publications of the Dominion Astrophysical Observatory Victoria, 14, 319
Pigatto, L., & Rosino, L. 1973, Mem. Soc. Astron. Ital., 44, 339
Pourbaix, D., Tokovinin, A. A., Batten, A. H., et al. 2004, A&A, 424, 727
Queloz, D., Allain, S., Mermilliod, J.-C., Bouvier, J., & Mayor, M. 1998, A&A, 335, 183
Richichi, A. 1989, A&A, 226, 366
Richichi, A., & Glindemann, A. 2012, A&A, 538, A56
Richichi, A., Baffa, C., Calamai, G., & Lisi, F. 1996, AJ, 112, 2786
Richichi, A., Chen, W. P., Fors, O., & Wang, P. F. 2011, A&A, 532, A101
Robinson, S. E., Ammons, S. M., Kretke, K. A., et al. 2007, ApJS, 169, 430
Schmitt, J. H. M. M., Kahabka, P., Stauffer, J., & Piters, A. J. M. 1993, A&A, 277, 114
Sierchio, J. M., Rieke, G. H., Su, K. Y. L., et al. 2010, ApJ, 712, 1421
Soderblom, D. R., Stauffer, J. R., Hudon, J. D., & Jones, B. F. 1993, ApJS, 85, 315
Stauffer, J. R. 1984, ApJ, 280, 189
Stauffer, J. R., Caillault, J.-P., Gagne, M., Prosser, C. F., & Hartmann, L. W. 1994, ApJS, 91, 625
Stauffer, J. R., Hartmann, L. W., Fazio, G. G., et al. 2007, ApJS, 172, 663
van Leeuwen, F. 2009, A&A, 497, 209
van Leeuwen, F., Alphenaar, P., & Brand, J. 1986, A&AS, 65, 309
Wang, J., Li, C., Zhao, J., & Jiang, P. 1996, Acta Astron. Sinica, 37, 68
White, R. J., Gabor, J. M., & Hillenbrand, L. A. 2007, AJ, 133, 2524
Zacharias, N., Monet, D. G., Levine, S. E., et al. 2005, VizieR Online Data Catalog I/1297