A&A 440, 1051–1060 (2005)
DOI: 10.1051/0004-6361:20042297

Astronomy & Astrophysics

Four new wide binaries among exoplanet host stars*

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Received 2 November 2004 / Accepted 31 May 2005

Abstract. In our ongoing survey for wide (sub)stellar companions of exoplanet host stars we have found 4 new co-moving stellar companions of the stars HD 114729, HD 16141, HD 196050 and HD 213240 with projected separations from 223 up to 3898 AU. The companionship of HD 114729 B, HD 196050 B and HD 213240 C is confirmed by photometry and spectroscopy, all being early M dwarfs. The masses of the detected companions are derived from their infrared *JHK* magnitudes and range between 0.146 and 0.363 $M_{\odot}$. Our first and second epoch observations can rule out additional stellar companions around the primaries from ~200 up to ~2400 AU (S/N = 10). In our survey we have found so far 6 new binaries among the exoplanet host stars. According to these new detections, the reported differences between single-star and binary-star planets with orbital periods short than 40 days remain significant in both the mass-period and eccentricity-period distribution. In contrast, all exoplanets with orbital periods longer than 100 days tend to display similar distributions.

Key words. stars: low-mass, brown dwarfs – planetary systems – stars: individual: HD 16141 – stars: individual: HD 114729 – stars: individual: HD 196050 – stars: individual: HD 213240

1. Introduction

Precise radial velocity (RV) search campaigns have found more than 130 exoplanets[1] orbiting G to M stars most of them in the solar neighborhood. Most exoplanets in the northern sky were detected, with the radial velocity method by the California & Carnegie planet search (Marcy & Butler 1996) and the ELODIE northern extrasolar planet search (Mayor & Queloz 1995). In the southern sky exoplanets are searched for by the Anglo-Australian planet search team (Tinney et al. 2001), in the CORALIE survey (Queloz et al. 2000) and by the recently started HARPS project (Pepe et al. 2004), among others.

Some of those exoplanets orbit stars that are themselves members of a multiple stellar system (binaries e.g. HD 19994 or triples e.g. 16 Cyg). The planets in those systems are interesting objects because they provide the possibility to study the effect of stellar multiplicity on planet formation, long-time stability and evolution of planetary orbits. Some authors have started to compare orbital properties of known planets in binaries with those of planets found in single stellar systems. There seem to be differences in the mass-period or eccentricity-period distributions between planets of single stars and planets of binaries as pointed out by e.g. Zucker & Mazeh (2002) or Eggenberger et al. (2004). However the number of known multiple stellar systems that harbor exoplanets is rather small (e.g. 15 shown by Eggenberger et al. 2004). Hence, statistical differences are sensitive to changes in the sample, either retracted planet detections, e.g. Desidera et al. (2004), or newly found systems with exoplanets as presented here. Furthermore stars listed as binaries in some double star catalogs cannot be confirmed by follow-up observations (see e.g. Sect. 3.3). Only systematic search programs for (sub)stellar companions can reveal the real fraction of wide (≥few arcsec) visual companions among all stars known to harbor planets. This is the first important step which must be done before analyzing statistical differences.

Several groups have already searched for (sub)stellar companions orbiting RV planet host stars with adaptive optics and found either companions around a few of them, like HD 114762 and τ Boo (Patience et al. 2004), Gl 86 (Els et al. 2001; Mugrauer & Neuhäuser 2005) or could exclude additional close faint companions (e.g. Macintosh et al. 2003). However, an interesting regime of companions with separations up to ~1000 AU is not accessible to those searches, due to their small field of view (FOV). Lowrance et al. (2002) presented a first new wide (750 AU) low-mass stellar companion ($m \sim 0.2\ M_{\odot}$) which was detected in the digitized plates of the

* Based on observations obtained on La Silla in ESO programs 70.C-0116(A), 71.C-0140(A), 72.C-0571(B), 73.C-0103(A) and on Mauna Kea in UKIRT program U/02A/16.

[1] Summarized at http://www.obspm.fr/encycl/encycl.html or http://exoplanets.org/

Palomar Obervatory Sky Survey. However, so far the whole sample of exoplanet host stars has not been surveyed homogeneously for such wide companions and therefore we initiated a systematic search campaign for wide faint companions of all exoplanet host stars. We use relatively large fields of view of up to 150 arcsec. Companions are detected by common proper motion first, and then are confirmed by photometry and spectroscopy (consistency of the apparent magnitude, color and spectral type of the companion at the distance of the primary).

Our effort already yielded two new wide stellar companions to the exoplanet host stars HD 75289 A (Udry et al. 2000) and HD 89744 A (Korzennik et al. 2000). HD 75289 B is a low-mass stellar companion (0.135 $M_{\odot}$) at a projected separation of 621 AU, detected with SofI[2] at the ESO New Technology Telescope (NTT) (see Mugrauer et al. 2004a). The companionship of HD 89744 B, proposed by Wilson et al. (2001), was confirmed with astrometry by UFTI[3] at the United Kingdom Infrared Telescope (UKIRT). In this case the companion mass ranges between 0.072 and 0.081 $M_{\odot}$, at an orbit with a projected separation of 2456 AU (see Mugrauer et al. 2004b).

In this work we present 4 new wide low-mass stellar companions which we detected in our ongoing survey orbiting HD 114729, HD 196050, HD 213240 and HD 16141. Section 2 describes the observations and reduction. In Sects. 3 to 5 we present astrometric, photometric and spectroscopic evidence for companionship. Section 6 summarizes the properties of the components of the newly found four binaries as well as their exoplanets and presents the detection limits of our observations.

2. Imaging, data reduction and calibration

All observations of our program are carried out in near infrared *H* band. Low-mass (sub)stellar companions are much brighter in the IR than in optical bands, hence detectable with a 4 m class telescope. In our survey we use two telescopes equipped with IR cameras. Imaging of targets in the northern sky is done with the 3.8 m UKIRT on Mauna Kea and the UFTI IR camera, equipped with a 1024×1024 HgCdTe-detector with a pixelscale of ~91 mas, i.e. 93 × 93 arcsec FOV. For the southern sky we use the 3.58 m NTT and its SofI IR camera, located at La Silla, Chile. SofI includes a 1024×1024 HgCdTe-detector with a pixelscale of ~144 mas, i.e. 147 × 147 arcsec FOV. All exoplanet host stars are relatively bright targets, much brighter than their possible companions. Hence, the bright primaries saturate the detectors, which makes a companion search impossible close to the primaries. To reduce this contamination we always use individual exposure times as short as possible, 1.2 s with SofI and 4 s with UFTI. Several of those images are taken at the same position and are stacked together by averaging. Then the telescope is moved to another position where the same procedure is repeated. Finally all images are flatfielded and combined to the final image with the ESO package ECLIPSE[4] which also provides the background subtraction. All images of an observing run were astrometrically calibrated by comparing the positions of the detected objects in our images with positions at the 2MASS[5] point source catalogue, which contains accurate astrometry of objects brighter than 15.2 mag in *H* ($S/N > 5$). In Table 1 we show the pixelscale as well as the derived detector orientation for SofI and UFTI observing runs from which data are presented in this work.

[2] Son of Isaac.

[3] UKIRT Fast-Track Imager.

[4] ESO C Library for an Image Processing Software Environment.

Table 1. The astrometrical calibration of all observing runs for which data are shown in this paper. The pixelscale PS and the detector position angle PA with their uncertainties are listed. The detector is tilted by PA from north to west.

Instrument	Epoch	PS [″]	PA [°]
UFTI	11/02	0.09098 ± 0.00043	0.770 ± 0.087
UFTI	10/03	0.09104 ± 0.00030	0.711 ± 0.083
$\mathrm{SofI_{small}}$	12/02	0.14366 ± 0.00016	90.069 ± 0.041
$\mathrm{SofI_{small}}$	06/03	0.14365 ± 0.00013	90.069 ± 0.032
$\mathrm{SofI_{small}}$	07/04	0.14356 ± 0.00011	90.047 ± 0.024
$\mathrm{SofI_{large}}$	07/04	0.28796 ± 0.00032	90.176 ± 0.045

3. Astrometry

In principle, all objects located close to an exoplanet host star could be real companions, i.e. they are all companion-candidates and therefore must be examined. However, most of these candidates will emerge as ordinary background stars randomly located close to but far behind the host star. A real companion shares the proper motion of its primary star because its orbital motion is much smaller than the common proper motion. Hence, astrometry is an effective method to detect and distinguish real companions from none moving background stars.

This section presents astrometric detection of four new wide co-moving companions. The astrometric test for companionship will be confirmed by photometry and spectroscopy in the following sections.

3.1. HD 114729

In our ongoing survey, HD 114729 was observed in December 2002 (epoch 12/02) and in epoch 06/03 with SofI. We found a companion-candidate only 8 arcsec northwest of the exoplanet host star, also detected by 2MASS in epoch 04/99. We used the *Starlink* software *GAIA* and its object detection routine to measure the separation and the position angle of the companion-candidate relative to the primary in our SofI images. The astrometry of both objects in the 2MASS image is provided by the 2MASS point source catalogue. If the candidate is a background object, it would have negligible proper motion and we would expect a change in separation and position angle due to the proper and parallactic motion of the exoplanet host star. This expected relative motion can be derived from the Hipparcos data of the primary ($\mu_{\mathrm{RA}} = -202.11 \pm 0.39$ mas yr^{-1}, $\mu_{\mathrm{Dec}} = -308.49 \pm 0.70$ mas yr^{-1} and $\pi = 28.57 \pm 0.97$ mas). However, the derived separation and position angle are constant in all three epochs. Hence, the detected companion-candidate

[5] 2 Micron All Sky Survey.

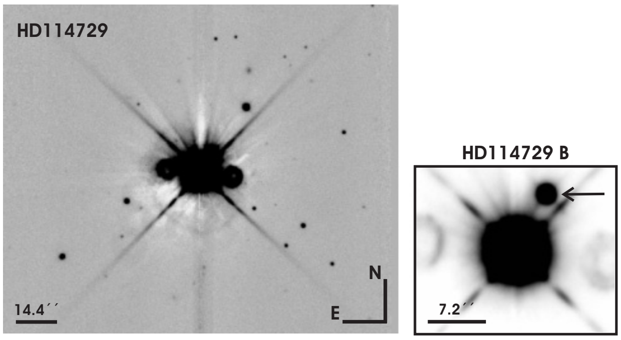

Fig. 1. *Left*: the SofI small field image of the planet host star HD 114729 (central bright star with diffraction spikes and reflections), taken in June 2003 in the *H* band. The total integration time is 10 min. Several faint companion-candidates can be seen. *Right*: magnified image of the central part of the FOV with different cuts. A companion-candidate, located ~8 arcsec northwest of the central star, is visible.

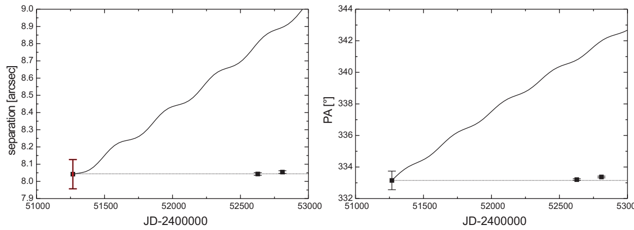

Fig. 2. The separation and the position angle between HD 114729 B and its primary in the 2MASS image (epoch 04/99) and our SofI images from epoch 12/02 and 06/03. If HD 114729 B is a non-moving background star, both parameters must change due to the well-known proper and parallactic motion of the primary star which is illustrated with a solid line. However, the measured separation and position angle are constant. With the given astrometric uncertainties the background hypothesis can be rejected at a 10σ level in separation and at a 15σ level in position angle. Hence, HD 114729 B is clearly co-moving with the exoplanet host star HD 114729 A.

Table 2. The separations and position angles of all detected companions candidates.

Companion	Epoch	Sep. [arcsec]	PA [°]
HD 114729 B	2MASS 03/99	8.042 ± 0.085	333.151 ± 0.590
small field	NTT 12/02	8.043 ± 0.008	333.202 ± 0.052
small field	NTT 06/03	8.054 ± 0.008	333.371 ± 0.052
HD 196050 B	2MASS 06/00	10.860 ± 0.085	174.360 ± 0.460
small field	NTT 06/03	10.880 ± 0.011	174.920 ± 0.040
small field	NTT 07/04	10.875 ± 0.011	174.872 ± 0.040
HD 213240 C	2MASS 08/99	95.628 ± 0.085	126.531 ± 0.051
large field	NTT 07/04	95.690 ± 0.077	126.523 ± 0.062
HD 16141 B	UFTI 11/02	6.221 ± 0.013	187.467 ± 0.091
	UFTI 10/03	6.191 ± 0.013	187.600 ± 0.087

is clearly co-moving and will be denoted as HD 114729 B (see Fig. 2 and Table 2).

Our first epoch SofI image shows several faint stars (S/N = 10 at $H \sim 18$ mag) that are invisible in the less sensitive 2MASS image (S/N = 10 at $H \sim 14.4$ mag). To derive the proper motion of these faint objects as well as to confirm that HD 114729 B is co-moving with the exoplanet host star, we obtained a second epoch SofI image only half a year later,

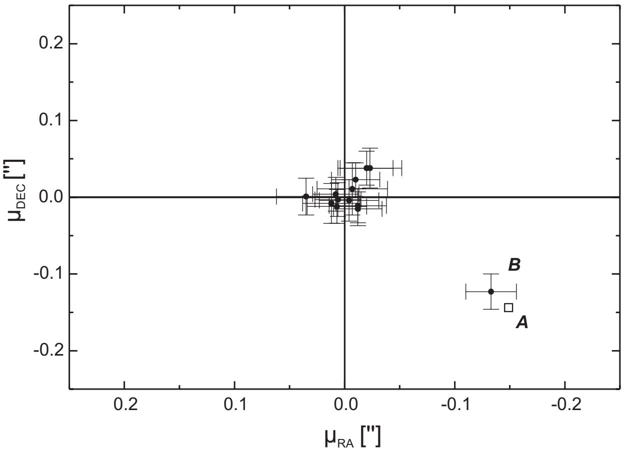

Fig. 3. The derived proper motion of all companion candidates detected in our NTT images ($S/N > 10$) from epochs 12/02 and 06/03. The expected proper motion of the primary is derived from Hipparcos data and is shown as a small square in the plot (A). HD 114729 B clearly shares the proper motion of the exoplanet host star. All other detected companion-candidates prove to be non-moving background stars.

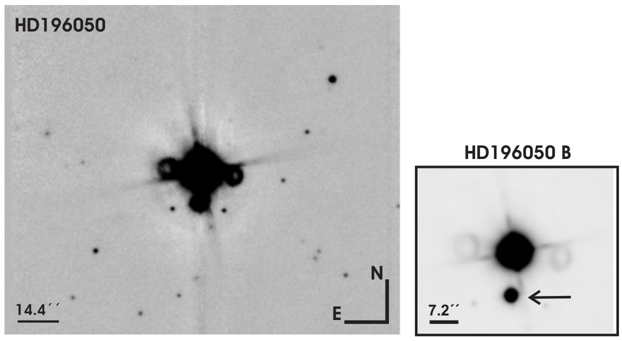

Fig. 4. *Left*: the SofI small field image of the planet host star HD 196050, obtained in epoch 06/03 in *H* band. The total integration is 10 min. Several faint companion-candidates are detected. *Right*: image of the central region of the field. The co-moving companion, HD 196050 B is located ~11 arcsec south of its primary star.

in epoch 06/03. The astrometry of all companion-candidates ($S/N > 10$) is measured with *ESO MIDAS* using Gaussian-fitting. All detected objects but HD 114729 B have proper motions which are negligible within the astrometric uncertainties (20 to 30 mas), hence are non-moving background stars. The derived proper motion of HD 114729 B is consistent with the expected value for a co-moving companion for the given epoch difference (see Fig. 3).

3.2. HD 196050

In June 2003 and July 2004 we observed HD 196050 with SofI. Figure 4 shows a faint star only ~11 arcsec south of the exoplanet host star, also detected by the 2MASS survey in June 2000. As described in the previous section we compared the relative position of the faint objects in 2MASS and our images (see Fig. 5 and Table 2). The detected companion-candidate emerges as a co-moving companion and will be

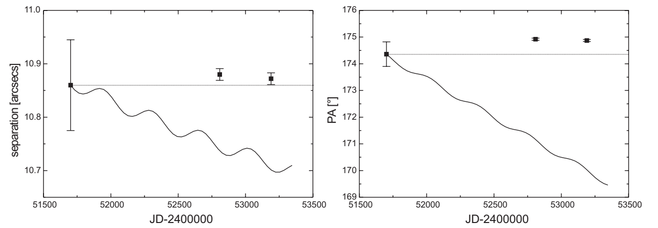

Fig. 5. Separation and position angle of HD 196050 B to its primary for the 2MASS image (epoch 06/00) and our SofI images (epoch 06/03 and 07/04). The expected variation of both parameters if HD 196050 B was a non-moving object is illustrated with a solid line. The separation and the position angle are constant within the astrometric uncertainty, as it is expected for a co-moving companion and significantly (11σ in position angle) different from the expected values for a non-moving HD 196050 B.

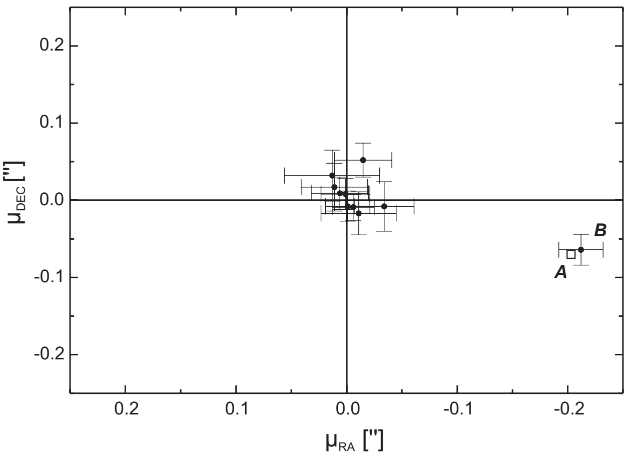

Fig. 6. The derived proper motion of all detected companion candidates ($S/N > 10$) shown in Fig. 4 for our two SofI images taken in epoch 06/03 and 07/04. The expected proper motion of the primary is derived with the well-known proper and parallactic motion of the primary (from Hipparcos data) and is shown as a small square in the plot (A). HD 196050 B is clearly co-moving to the exoplanet host star, but all other detected companion-candidates emerge as non-moving background stars.

denoted as HD 196050 B. As expected for a co-moving companion, the separation from the primary as well as its position angle is constant within the astrometric uncertainty for all given epochs. If HD 196050 B is not co-moving, the position angle must significantly change (11σ) according to Hipparcos data of HD 196050 A ($\mu_{\rm RA} = -190.97 \pm 0.71$ mas yr^{-1}, $\mu_{\rm Dec} = -64.27 \pm 0.57$ mas yr^{-1} and $\pi = 21.31 \pm 0.91$ mas).

The first epoch SofI image shows several faint companion-candidates, which are all well detected with $S/N \geq 10$, hence accurate astrometry is available for them. In July 2004 we obtained the second epoch SofI image and we determined the proper motion of all detected companion-candidates as described in the previous section. The derived proper motion of HD 196050 B is consistent with its primary star HD 196050 A (see Fig. 6) as it is expected for a co-moving companion. Furthermore, with the accurate NTT astrometry we can clearly rule out all other stars as co-moving with the exoplanet host star.

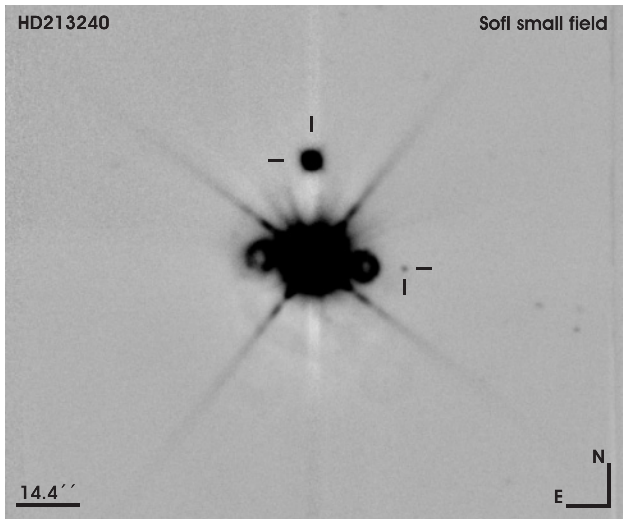

Fig. 7. The SofI small field image of the exoplanet host star HD 213240. It was taken in July 2004 in H band with a total integration of 10 min. Only two companion-candidates both are marked in the image are detected with $S/N \geq 10$ and offer a sufficient astrometry to check common proper motion with the bright primary. The separation of both companion-candidates to HD 213240 varies over time as expected from the well-known proper and parallactic motion of the exoplanet host star, hence they are non-moving background stars.

3.3. HD 213240

We obtained our first epoch SofI image in December 2002 and a second epoch follow up in July 2004. Both images are taken as usual in the SofI small field. Only two companion-candidates, both marked in Fig. 7, are detected ($S/N \geq 10$) with sufficient astrometric accuracy. The separation of the brighter candidate north of HD 213240 significantly varies from 22.427 ± 0.023 in epoch 2002 to 22.684 ± 0.024 arcsec. In addition, this companion-candidate is also listed in the UCAC2 catalogue with a proper motion of $\mu_{\rm RA} = 65.2$ mas yr^{-1}, $\mu_{\rm Dec} = -10.8$ mas yr^{-1}, hence this object is clearly not co-moving with the exoplanet host star. For the fainter companion-candidate the separation varies from 20.291 ± 0.030 in epoch 2002 to 20.022 ± 0.030 arcsec in epoch 2004. This change in separation is expected from the Hipparcos astrometric data of HD 213240 ($\mu_{\rm RA} = -135.16 \pm 0.66$ mas yr^{-1}, $\mu_{\rm Dec} = -194.06 \pm 0.47$ mas yr^{-1} and $\pi = 24.54 \pm 0.81$ mas), i.e. this faint object is also clearly not co-moving.

However, HD 213240 is listed in the Washington Double Star Catalog (WDS) as a binary with a $V = 12$ mag companion at the position angle of 284° and a separation of 19.8 arcsec (epoch 1901). Actually, the fainter companion-candidate is located roughly at that position (PA = 265.68 ± 0.050°; separation = 20.022 ± 0.030 arcsec in July 2004) but as we have shown above it is clearly not co-moving with HD 213240. Furthermore, its H magnitude derived from our H band images is $H = 17.517 \pm 0.020$ mag, which is much too faint for a $V = 12$ mag object at the distance of HD 213240. When we extrapolate the proper motion of HD 213240 back to the epoch of the WDS entry (1901) and also take into account the proper motion of the brighter companion-candidate today

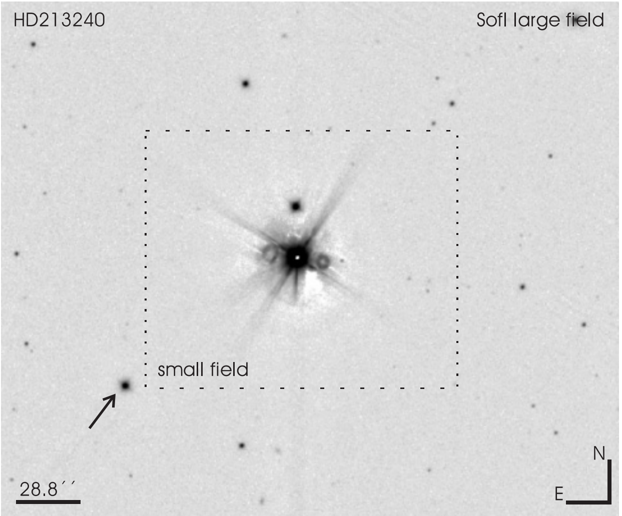

Fig. 8. The SofI large field *H* band image of HD 213240 taken in July 2004. The total integration time is 7 min. Several companion-candidates are detected. An arrow points to the co-moving companion HD 213240 C which was detected by comparing this SofI image with the image from the 2MASS survey.

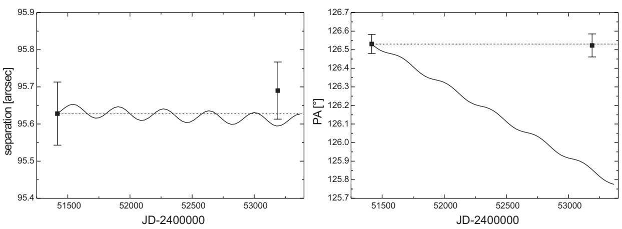

Fig. 9. The separation and the position angle between HD 213240 C and its primary for the 2MASS image (epoch 08/99) and our first epoch SofI large field image (epoch 07/04). Separation and position angle are constant in both observing epochs typical for a co-moving object. Furthermore if HD 213240 C would be non-moving the position angle must significantly change following the well-known proper and parallactic motion of HD 213240 A (see solid lines).

located north of the exoplanet host star, we derive a position close to the entry in the WDS for PA and separation (PA ~ 281.1°; separation ~20.4 arcsec). So, it is most likely that this object was denoted as the secondary in the WDS.

In addition to our small field imaging we also observed HD 213240 with SofI in the large field mode in July 2004. The given FOV is twice as large as the small field, i.e. 295 × 295 arcsec (see Fig. 8). Many faint stars can be seen in the image. By comparing our image with the 2MASS survey from epoch 08/99 we found a co-moving companion. Its separation and position angle with respect to the primary are constant within the astrometric uncertainty (see Fig. 9 and Table 2). For a non-moving object both parameters must change due to the proper and parallactic motion of the exoplanet host star. This expected variation can significantly (8σ in position angle) be ruled out for the detected companion (see doted lines in Fig. 9). Hence, this companion is clearly co-moving and will be denoted as HD 213240 C in the following, because B is already used by WDS.

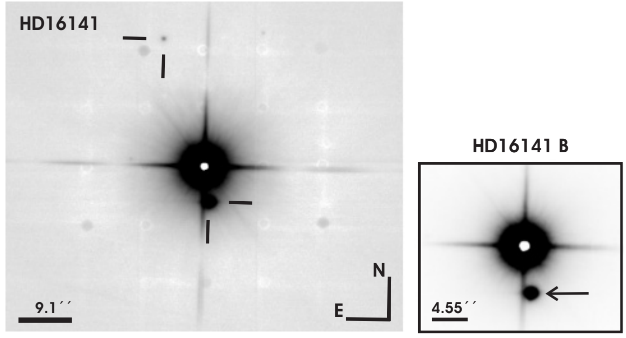

Fig. 10. *Left*: the UFTI *H* band image obtain in October 2003. The integration time is 9.6 min. Two companion-candidates are detected with good astrometry precision both indicated with markers. *Right*: the central part of the image zoomed and rescaled. The newly found co-moving companion HD 16141 B is visible ~6 arcsec south of the exoplanet planet host.

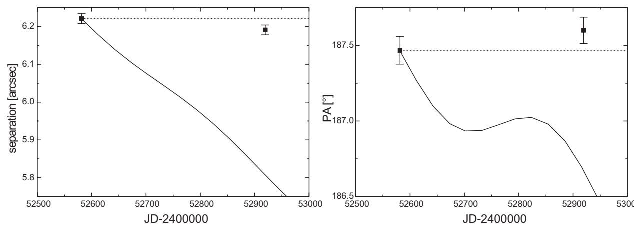

Fig. 11. The separation and the position angle of HD 16141 B both UFTI/UKIRT images (epoch 11/02 and 10/03). Separation and position angle are constant in both observing epochs as expected for a co-moving companion and are significantly different to the expected values if HD 16141 B was a non-moving background object using the well-known proper and parallactic motion of the primary (see solid lines).

3.4. HD 16141

We observed HD 16141 for the first time in November 2002, and one year later in October 2003 using UFTI/UKIRT. Only two companion-candidates are detected with good astrometric precision and are marked in the left image of Fig. 10. We measured separation and position angle of the two candidates relative to the exoplanet host star. The separation of the fainter object north of HD 16141 increased from 22.394 ± 0.045 mas in November 2002 to 22.860 ± 0.046 mas in October 2003 consistent with the proper and parallactic motion of HD 16141 ($\mu_{\rm RA} = -156.89 \pm 1.39$ mas yr^{-1}, $\mu_{\rm Dec} = -437.07 \pm .74$ mas yr^{-1} and $\pi = 27.85 \pm 1.39$ mas). Hence, this is an ordinary background object. The separation and position angle of the candidate 6 arcsec south of HD 16141 is shown in Fig. 11 and in Table 2. Both separation and position angle are constant in both epochs and are significantly different (21σ in separation and 7σ in position angle) from the expected data if the candidate was non-moving. Hence, we can conclude that the candidate is clearly co-moving to HD 16141, i.e. it will be named HD 16141 B.

Table 3. 2MASS, SofI and UFTI photometry of the newly found companions. The 2MASS photometry of HD 213240 C and HD 196050 B are consistent with our SofI photometry. HD 114729 B is still slightly contaminated. The closest detected companion HD 16141 B is badly contaminated by more than 1.5 mag.

Companion	Band	m_{2MASS}	Camera	$m_{SofI/UFTI}$
HD 16141 B	J	9.271 ± 0.136	–	–
Sep. ~ 6″	H	8.472 ± 0.325	UFTI	10.062 ± 0.049
	K_S	8.766 ± 0.124	–	–
HD 114729 B	J	10.111 ± 0.069	SofI	10.768 ± 0.039
Sep. ~ 8″	H	9.718 ± 0.067	SofI	10.255 ± 0.047
	K_S	9.517 ± 0.046	SofI	10.008 ± 0.077
HD 196050 B	J	10.619 ± 0.043	SofI	10.777 ± 0.042
Sep. ~ 11″	H	10.158 ± 0.037	SofI	10.066 ± 0.057
	K_S	9.835 ± 0.030	SofI	9.843 ± 0.079
HD 213240 C	J	12.362 ± 0.025	–	–
Sep. ~ 96″	H	11.742 ± 0.026	SofI	11.789 ± 0.090
	K_S	11.465 ± 0.025	–	–

4. Photometry

In the previous section we have presented astrometric evidence for companionship of four new companions. In special cases, apparently co-moving objects may not be physically bound companions, e.g. in case of a slowly moving foreground or fast moving background object. Hence, it is necessary to confirm co-moving objects as true companions by e.g. photometry. This section presents the obtained photometry of all newly found companions derived from our own observations as well as from the 2MASS point source catalog.

The angular separation of the detected companions ranges between 96 arcsec for HD 213240 C and only 6 arcsec for HD 16141 B. The smaller the separation, the stronger the photometric contamination by light from the nearby bright star. Therefore we obtained the photometry of all four companions in our H band images and compared it with the 2MASS photometry. In Table 3 we have summarized all photometric data. For HD 213240 C and HD 196050 B the 2MASS photometry is consistent with the SofI photometry, as expected for such wide separated companions (more than 10 arcsec of separation). HD 114729 B, with a separation of 8 arcsec, is slightly contaminated in 2MASS. We obtained additional SofI photometry to confirm this result also in J and Ks. The 2MASS photometry is about 0.5 mag brighter in J, H, Ks than our SofI photometry, as expected for close companions observed with the large 2MASS pixelscale of 1 arcsec per pixel. Finally, HD 16141 B, with a separation of only 6 arcsec, is badly contaminated by more than 1.5 mag in H. Hence, we do not use 2MASS data for this companion.

With the transformation of Carpenter (2001) we derive $J - K$ for all companions for which we have accurate J and Ks magnitudes. We also derived the absolute H magnitude, using the measured apparent H magnitude and the Hipparcos parallax. We plot all companions in a color–magnitude diagram which is shown in Fig. 12 (data are summarized in Table 4). In addition, the figure shows the theoretical isochrone for 5 Gyr from Baraffe et al. (1998) models. The color and the derived absolute magnitudes, based on the distance of the primary, are consistent with low-mass stellar companions. Therefore, we conclude that the photometry is consistent with the companionship assumption.

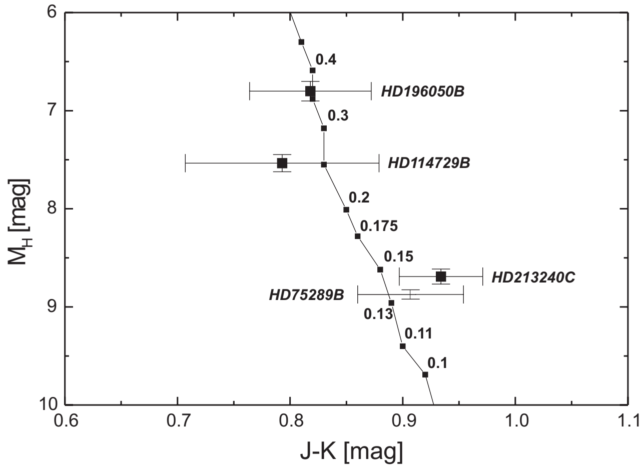

Fig. 12. A color–magnitude diagram of all detected companions for which J, H and Ks infrared magnitudes are known. A isochrone from Baraffe et al. (1998) models is illustrated as solid line with dots which show the companion-mass in units of solar mass. All companions are consistent with low-mass stellar objects at the distance of the primaries. In addition we also show HD 75289 B from Mugrauer et al. (2004a).

Table 4. $J - K$ color and absolute H magnitudes of the detected companions, shown in Fig. 12.

Companion	$J - K$ [mag]	M_H [mag]
HD 114729 B	0.793 ± 0.086	7.535 ± 0.088
HD 196050 B	0.818 ± 0.054	6.801 ± 0.100
HD 213240 C	0.934 ± 0.037	8.691 ± 0.077
HD 75289 B	0.907 ± 0.047	8.873 ± 0.048

5. Spectroscopy

Photometry may not be sufficient for confirmation of a co-moving companion because reddened background giants can be as red as intrinsically red low-mass companions. To confirm that the newly found companions are really dwarfs we obtained IR spectra of HD 114729 B, HD 196050 B and HD 213240 C in June 2003 and July 2004 with SofI in spectroscopic mode. We used long slit spectroscopy with a slit width of one arcsec, and the red grism covering the wavelength range from 1.53 to 2.52 μm. The dispersion is 10.22 Å per pixel with an IR HgCdTe detector in the large field mode (288 mas pixel scale) providing a resolving power of $\lambda/\Delta\lambda \approx 588$.

Background subtraction was obtained by nodding between two positions along the slit, as well as by a small jitter around those two positions, to avoid individual pixels always seeing the same part of the sky. All images were flat fielded with a standard dome flat and wavelength calibrated with a Xe lamp. After flatfielding, all individual spectra, each with a total integration time of 1 min, were averaged. We used standard IRAF routines for background subtraction, flat fielding and averaging all individual spectra.

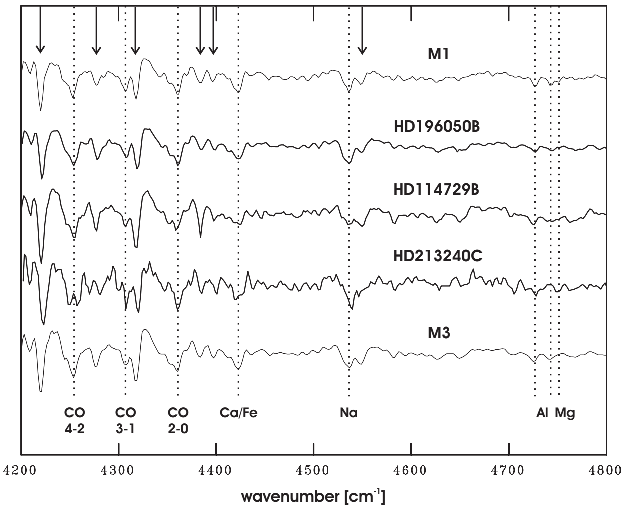

Fig. 13. *K* band SofI spectra of the detected companions HD 114729 B, HD 196050 B and HD 213240 C. Furthermore we show comparison spectra of spectral type M1V and M3V. The arrow indicate telluric features.

Figure 13 shows the normalized *K* band spectra of the detected companions and two comparison spectra (HIP 80268 $B-V = 1.458$ M1V, HIP 5496 $B-V = 1.568$ M3V). The strongest lines in the spectra are from molecular bands of the first CO overtone, extending from 4360 cm^{-1} to the low frequency side of the spectrum. Strong atomic features of Ca/Fe (4415 cm^{-1}) and Na (4530 cm^{-1}) are visible, as well as weak lines of Al at 4724 and 4740 cm^{-1} and Mg at 4747 cm^{-1}. Hence all three companions are of spectral type early M, which is also consistent with the measured colors. Due to CO bands which are only slightly stronger than the atomic features of Na and Ca/Fe we can conclude that all three companions are dwarfs, hence luminosity class V.

6. Discussion

6.1. The primaries and their planets

6.1.1. HD 16141

HD 16141 is a slow rotating chromospherically inactive G5IV star, located in the constellation Cetus. With the Keck High-Resolution Echelle Spectrograph Marcy et al. (2000) found an exoplanet ($m\sin(i) = 0.215\,M_{\rm Jup}$) orbiting its parent star on a 0.35 AU eccentric orbit ($e = 0.28$) with an orbital period of only 0.21 yr. Laws et al. (2003) determined that the exoplanet host star is between 3.2 and 6.7 Gyr old and has a mass of 1.22 $M_\odot$.

6.1.2. HD 114729

Butler et al. (2003) reported the detection of an exoplanet orbiting the star HD 114729, a result of the Keck Precision Doppler Survey. The planet has a minimum-mass $m\sin i(i) = 0.84\,M_{\rm Jup}$ and revolves around its host star on a 3.11 yr eccentric orbit, with a semi-major-axis (a) of 2.08 AU and an eccentricity (e) of 0.32. The parent star is located in Centaurus, listed as G3V by SIMBAD and G0V by Hipparcos. The latter classification was assigned by Butler et al. (2003) derived from their Keck spectra. The star is chromospherically quiet and Butler et al. (2003) estimate its age to be approximately 6 Gyr.

6.1.3. HD 196050

HD 196050 is a G3V star located in the southern constellation Pavo. The discovery of an exoplanet was reported firstly by Jones et al. (2002) in the Anglo-Australian Planet Search (AAPS) and confirmed later by Mayor et al. (2004) in the CORALIE planet-search programm. The detected exoplanet ($m\sin(i) = 2.8\,M_{\rm Jup}$) revolves its host star on an eccentric 3.56 yr orbit ($e = 0.19$; $a = 2.4$ AU). The parent star is chromospherically quiescent and is not detected to be variable by Hipparcos. It is used as an infrared spectroscopic standard by the ESO/NTT team on La Silla. The mass and age of HD 196050 was determined by Mayor et al. (2004) to be 1.1 $M_\odot$ and 1.6 Gyr, respectively.

6.1.4. HD 213240

HD 213240 is a G0V star located in the southern constellation Grus. Its mass is 1.22 $M_\odot$ and its age lies between 2.7 and 4.6 Gyr, with the stellar parameters derived by Santos et al. (2001). The same group reported the detection of an exoplanet with a minimum mass of 4.5 $M_{\rm Jup}$ which revolves around HD 213240 on a 2.61 yr eccentric ($a = 2.03$ AU, $e = 0.45$) orbit. Although the minimum mass of the close companion is high compared to most of the detected exoplanets, Santos et al. (2001) noted that the probability that the companion is actually a brown dwarf and not a planet is quite low, only around 5%, and thus the planetary assumption seems the most probable.

6.2. Statistical properties of exoplanets in binaries

We can group all exoplanets in two populations, namely exoplanets found in binaries (binary-star planets) and planets orbiting a single star (single-star planets). So far we have detected 6 further binaries among the exoplanet host stars in our survey, i.e. the sample size of binaries among exoplanet host stars is extended by 40% compared to Eggenberger et al. (2004) who describe differences in the properties (period, mass, eccentricity) of the two exoplanet populations.

In the mass-period diagram Zucker & Mazeh (2002) pointed out that for periods shorter than 40 days the most massive planets are binary-star planets and all known single-star planets have minimum-masses $m\sin(i) < 2\,M_{\rm Jup}$. Eggenberger et al. (2004) count 3 binary-star planets with $m\sin(i) > 2\,M_{\rm Jup}$ and only 2 binary-star planets but 20 single-star planets with $m\sin(i) < 2\,M_{\rm Jup}$. Selection effects are taken into account by discarding from the count exoplanets with $K < 15$ m/s. If no difference in the mass-period distribution of the both exoplanet populations is assumed, the probability for the given binary planet distribution is only 0.44%

In the eccentricity-period diagram both populations seems to be different as well. Eggenberger et al. (2004) count

5 binary-star planets with $e < 0.05$ and single-star planets appear to be more or less equally distributed, 9 with $e < 0.05$ and 11 with $e > 0.05$. They conclude that with a probability of 3.77% the given binary-star planet distribution can be explained assuming that both populations are identical.

Among the new binary-star planets, HD 75289 b ($m \sin(i) = 0.42\,M_{\rm Jup}$, $a = 0.046$ AU, $e = 0.024$) revolves its host stars with an orbital period of less than 40 days, hence modifies the mass-period and eccentricity-period diagram of the close binary-star planets (see Fig. 14). The derived probabilities are updated to 0.87%[6] in the mass-period diagram and 1.70%[7] in the eccentricity-period diagram, respectively.

The fact that the mass of the planet around HD 75289 is less than $2\,M_{\rm Jup}$ slightly decreases the statistical significance of the *mass* difference between the short-period single-star and binary-star planets. However, the significance remains still high. On the other hand the difference in the eccentricity distribution becomes slightly larger, supporting the conjecture that the multiplicity of the exoplanet host stars indeed influences either the planet formation process or the long-term orbital evolution of close exoplanets. The observed differences in the mass- and eccentricity-period diagrams are expected if a migration process took place in the history of the planetary systems. The multiplicity of the host star should speed up the migration process, yielding more massive short period planets on low-eccentric orbits compared to exoplanets in single star systems (see e.g. Kley 2000).

Eggenberger et al. (2004) also describe a difference in the mass-period distribution between single-star and binary-star planets with orbital periods longer than 100 days. They count 10 binary-star planets with $m \sin(i) < 5\ M_{\rm Jup}$ but no more massive binary-star planets. The retracted planet HD 219542 b (Desidera et al. 2003) was already excluded there because of $K = 13$ m/s and is not shown in Fig. 14. In contrast there are 46 single-star planets with $m \sin(i) < 5\ M_{\rm Jup}$ and 21 with $m \sin(i) > 5\,M_{\rm Jup}$. Assuming again the same distribution for both populations the probability of finding 10 planets with $m \sin(i) < 5\ M_{\rm Jup}$ but 0 with with $m \sin(i) > 5\ M_{\rm Jup}$ is 3.25%.

The new binary-star planets HD 213240 b, HD 196050 b and HD 114729 b are all located in this region of the mass-period diagram, hence now there are 13 long period binary planets known with $m \sin(i) < 5\,M_{\rm Jup}$. HD 89744 b ($m \sin(i) = 7.2\,M_{\rm Jup}$, $a = 0.88$ AU, $e = 0.70$) is the first known long-period massive planet, found by us to reside in a binary system. With updated statistics the derived probability of having the given masses of the binary-star planets coming from the same distribution for both exoplanet populations increases from 3.25% to 4.73%[8], i.e. the significance of the reported statistical difference is weakened. For orbital periods longer than 100 days, binary- and single-star planets display the same distributions, as was already apparent from the eccentricity-period distribution. Therefore, it seems as if the host star multiplicity does not affect the orbital properties of the long-period exoplanets.

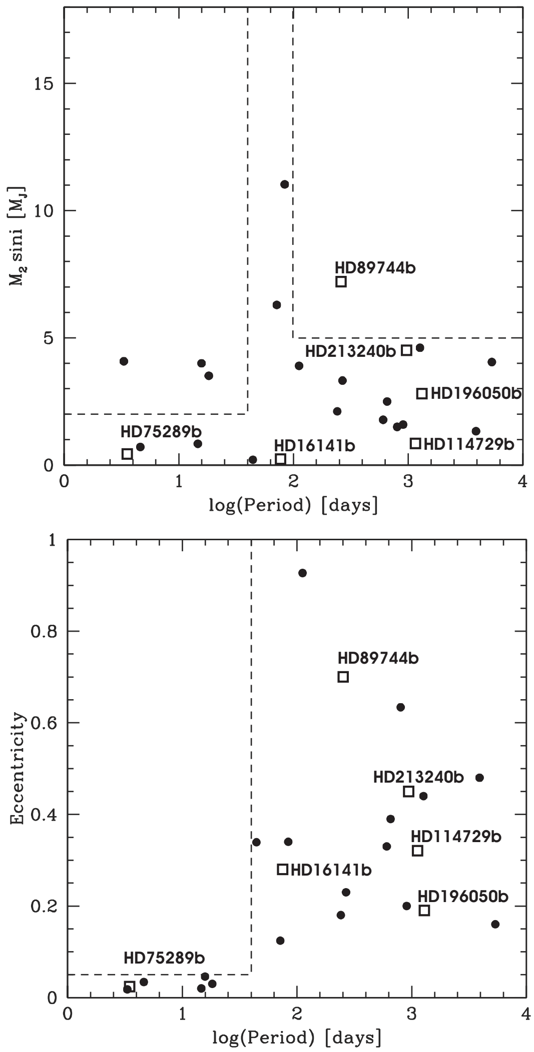

Fig. 14. The updated mass-period (*upper panel*) and eccentricity-period distribution (*lower panel*) of Eggenberger et al. (2004). All new binary-star planets are marked with black squares and all binary-star planets from Eggenberger et al. (2004) are shown with dark dots. HD 213240 b, HD 196050 b, and HD 114729 b exhibit minimum masses smaller $5\,M_{\rm Jup}$ comparable to all other binary-star planets found with periods longer than 100 days. However with $M \sin(i) = 7.2\,M_{\rm Jup}$ HD 89744 b is the first known exception from that rule. HD 75289 b exhibits a low eccentricity consistent with all other known binary-star planets on orbits shorter 40 days. The eccentricities of HD 213240 b, HD 196050 b, HD 114729 b and HD 89744 b are widely spread from 0.19 up to 0.7, consistent with the eccentricity distribution of other long periodic binary-star as well as single-star planets. The eccentricity distribution of both exoplanet populations seems to be similar for orbital periods longer than 100 days.

6.3. The newly detected secondaries

All newly found companions presented in this work are clearly co-moving with their primaries, the exoplanet host stars. For HD 114729 B, HD 196050 B and HD 213240 C we have also

[6] Hypergeometric distribution: $\binom{22}{3}\binom{3}{3}/\binom{25}{6} = 0.87\%$.

[7] Hypergeometric distribution: $\binom{14}{6}\binom{11}{0}/\binom{25}{6} = 1.70\%$.

[8] Hypergeometric distribution: $\binom{56}{13}\binom{21}{1}/\binom{77}{14} = 4.73\%$.

Table 5. Projected separation and derived companion masses.

Companion	Proj. separation [AU]	Mass [$M_\odot$]
HD 16141 B	223 ± 11	0.286 ± 0.017
HD 114729 B	282 ± 10	0.253 ± 0.011
HD 196050 B	511 ± 22	0.363 ± 0.018
HD 213240 C	3898 ± 129	0.146 ± 0.005

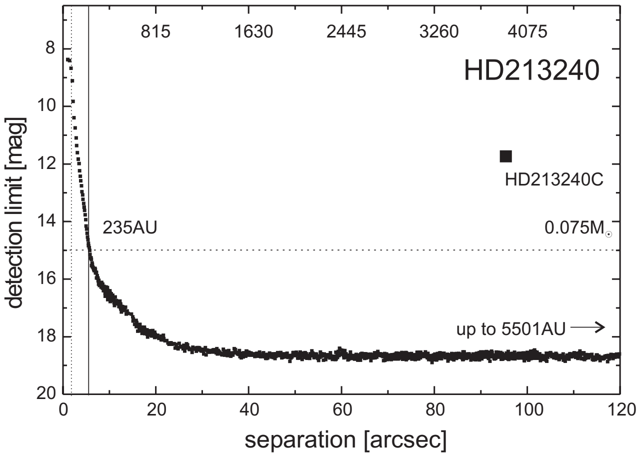

Fig. 15. Detection limit of SofI large field in H band for a range of separation given in arcsec at the bottom and as projected separation in AU at the top. At ~1 arcsec saturation occurs (doted line). All stellar companions ($m \geq 0.075\,M_\odot$) are detectable beyond the distance illustrated by the straight line.

obtained J, H, K_s photometry as well as K band spectra. The derived spectral types and the measured infrared colors and magnitudes are consistent with low-mass stellar objects at the well-known distances of the exoplanet host stars. Hence, companionship is also confirmed by photometry and spectroscopy. For HD 16141 we only have astrometric evidence for companionship. However the chance of finding a co-moving object at a separation of only 6 arcsec at a galactic latitude of ~−56° is negligible. To confirm our detection, follow-up spectroscopy is planned for this companion.

We derive the companion masses from the given infrared colors and Hipparcos parallaxes of the primaries using the Baraffe et al. (1998) isochrones for a system age of 5 Gyr. The age uncertainty of the primaries is not very important, because magnitudes of low-mass stellar companions are very stable for an age range between 1 and 10 Gyr. In Table 5 we summarize the derived parameters of the detected co-moving companions.

With the derived companion masses, the primary mass (~1 $M_\odot$) and the companion separations we can compute the expected RV variation of the primary induced by the presence of the wide companions. The maximal yearly variation of the RV is ~1 m/s for HD 16141, the closest detected companion, being probably detectable as linear trend in the RV after a decade of precise radial velocity measurements.

Figures 15 and 16 shows the achieved SofI and UFTI detection limits ($S/N = 10$), which reach ~18 mag in H, and therefore enables the detection of substellar companions down to $M_H \sim 15$ mag, which is translated to a mass of ~60 $M_{\rm Jup}$ according to the Baraffe et al. (2003) models. Objects

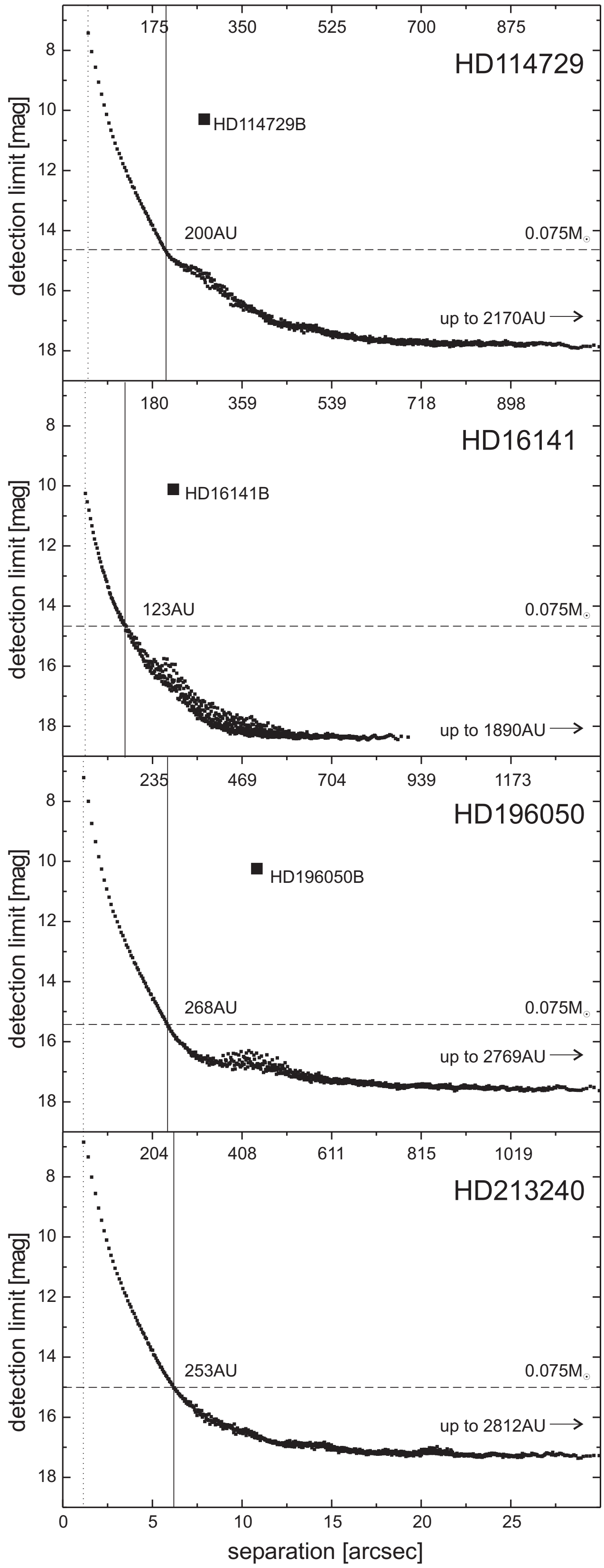

Fig. 16. Detection limits of SofI small field and UFTI images in H band for a range of separations given in arcsec at the bottom and as projected separation in AU at the top of each individual plot. At ~1 arcsec saturation occurs (doted line). All stellar companions ($m \geq 0.075\,M_\odot$) are detectable beyond the distance illustrated by the straight lines in each individual plot.

at distances of up to ~60 arcsec were observed twice but no further co-moving companion could be identified. Further stellar companions ($m \geq 75\, M_{\rm Jup}$) can be ruled out for a projected separation from ~200 AU up to ~2400 AU.

Acknowledgements. We would like to thank the technical staff of the ESO NTT and Joint Astronomy Center for help and assistance in carrying out the observations and A. Szameit who carried out some of the observations. We made use of the 2MASS public data releases as well as the Simbad database operated at the Observatoire Strasbourg. T.M. thanks the Israel Science Foundation for a support through grant No.03/233.

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