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High-contrast imaging search for stellar and substellar companions of exoplanet host stars

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ABSTRACT

We present the results of our high-contrast imaging survey of close stellar and substellar companions of exoplanet host stars, carried out with the adaptive optics imager NACO at the ESO Paranal observatory, in Chile. In total, 33 exoplanet host stars were observed with NACO in the *Ks*-band. New comoving companions could be identified close to the stars HD 9578, HD 96167, and HD 142245. The newly detected companions exhibit masses between 0.21 and 0.56 $M_{\odot}$ and are located at projected separations from their primaries between about 190 and 510 au. In the case of HD 142245, we found evidence that the detected companion is actually a close binary itself with a projected separation of only about 4 au, i.e. HD 142245 might be a hierarchical triple stellar system, which hosts an exoplanet, a new member in the short list of such systems, presently known. In our imaging campaign, a limiting magnitude of $Ks = 18.5$ mag is reached in average in the background noise limited region around our targets at projected separations beyond about 100 au, which allows the detection of substellar companions with masses down to about 60 M_{Jup}. With our NACO observations we can rule out additional stellar companions at projected separations between about 30 and 370 au around the observed exoplanet host stars.

Key words: techniques: high angular resolution – binaries: close – binaries: visual – stars: imaging.

1 INTRODUCTION

During the last two decades more than thousand planets could be detected among about the same number of stars in the solar neighbourhood. Most of these exoplanets were identified indirectly either by radial-velocity or by photometric transit search campaigns. Further exoplanets could be detected by timing and microlensing surveys. Some exoplanets even could be imaged next to their host stars in the near-infrared, using high-contrast adaptive optics (AO) imagers at 8–10 m class telescopes, e.g. NACO (see Lenzen et al. 2003; Rousset et al. 2003), which is installed at the Very Large Telescope (VLT), operated by the European Southern Observatory (ESO), in Chile.

Most of the exoplanet host stars are isolated single stars, but several of them emerged as components of multiple stellar systems, mainly detected by ongoing seeing-limited, high-contrast AO, and lucky-imaging surveys, as well as catalogues searches (see among others e.g. Eggenberger et al. 2007; Mugrauer & Neuhäuser 2009; Ginski et al. 2012; Bergfors et al. 2013).

From theory it is expected that a stellar companion of an exoplanet host stars alters the formation process of exoplanets, which occurs within a gas and dust disc around the star (see e.g. Kley & Nelson 2008, or for a recent review Thebault & Haghighipour 2014). In addition, the gravitational perturbations induced by the companion star will alter the long-term orbital evolution of the exoplanet (see e.g. Wu, Murray & Ramsahai 2007). In particular, the closest stellar systems with exoplanets are most intriguing, because the gravitational perturbations of the stellar companion on the planet bearing disc at first and on formed planets afterwards is expected to be maximal.

In this context the results of multiplicity studies of exoplanet host stars are of great importance because their results can eventually be used to explore the impact of the stellar multiplicity on the formation of exoplanets and the evolution of their orbits, and therefore allow us to test formation and evolution theories of planets in multiple stellar systems.

Several differences between the orbital parameters and masses of exoplanets in stellar systems and of those orbiting single stars were already reported in the literature, all of them concluded from results of imaging surveys, see e.g. Eggenberger, Udry & Mayor (2004), Mugrauer, Neuhäuser & Mazeh (2007), Roell et al. (2012), and Kaib, Raymond & Duncan (2013).

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† Based on observations obtained at the Paranal observatory in ESO programmes 089.C-0134(A), 090.C-0125(A), and 091.C-0429(A).

Most of the detected companions of exoplanet host stars are low-mass main-sequence stars with projected separations of a few tens up to several thousand astronomical units (au), but also brown and white dwarf companions of these stars were identified via direct imaging observations (see e.g. Mugrauer & Neuhäuser 2005; Mugrauer et al. 2006, 2007). In some cases the detected companions even turned out to be close binaries themselves, making these systems to hierarchical triples, which harbour exoplanets (Mugrauer et al. 2005; Ginski et al. 2013). Furthermore, one exoplanet could be detected even in a possible quadruple system, namely Kepler-64 (alias PH1), as reported by Schwamb et al. (2013).

The majority of exoplanets found in stellar multiple systems exhibit S-type orbits. In the systems HD 20782 AB, and XO-2 AB, exoplanets were even detected around both components of these systems, see Jones et al. (2006), Mayor et al. (2011), and Desidera et al. (2014). In addition, exoplanets were also found on P-type orbits around close eclipsing binary stars, see e.g. Kepler-413(AB), recently reported by Kostov et al. (2014).

In this paper, we present the results of our high-contrast imaging survey of close companions of exoplanet host stars, which is carried out with NACO at the ESO Paranal observatory, in Chile. In the following section, we describe in detail the observations, which were conducted in the course of our imaging campaign, summarize the astrometric calibration for all observing runs, and present the astrometric and photometric measurements of all detected comoving companions. Finally, in the last section of this paper we derive and discuss the properties of the detected companions, and present the achieved detection limits for all exoplanet host stars, which were observed in our NACO survey.

2 NACO IMAGING SURVEY FOR CLOSE (SUB)STELLAR COMPANIONS OF EXOPLANET HOST STARS

In the course of our ongoing multiplicity studies of exoplanet host stars on the southern sky, we carried out high-contrast imaging observations with the AO imager NACO at the ESO Paranal observatory, in Chile. We selected all those exoplanet host stars as targets, whose multiplicity was not investigated for close companions before, using AO imagers at 8–10 m class telescopes.

In addition, in order to achieve an optimal wavefront correction with NACO under standard seeing conditions at the ESO Paranal Observatory only those exoplanet host stars were selected as targets, which are observable from Paranal under low airmasses ($AM < 2$), and which exhibit sufficient brightness ($V < 9.8$ mag, $Ks < 7.2$ mag) to be usable as natural AO reference sources for wavefront sensing and correction. The observed exoplanet host stars are all nearby stars, which exhibit an average distance of 52 pc (optimal targets for the detection of close stellar companions using NACO at the VLT), and sufficiently high proper motions (172 mas yr^{-1} in average) to identify comoving companions already after a few months up to one year of epoch difference. The properties of our targets are summarized in Table 1.

Table 1. The properties of all exoplanet host stars observed in our NACO survey. We list the apparent *V*- and *Ks*-band magnitudes and SpTs of all our targets, together with the average seeing condition during the observations of the targets, the full width at half-maximum (FWHM) of the stellar PSF of the exoplanet host stars in our NACO images, as well as the number of detected companion candidates for each target.

Name	*V* (mag)	*Ks* (mag)	SpT	Seeing (arcsec)	FWHM (mas)	N_{cc}
HD 8535	7.7	6.4	G0V	0.88	82	0
HD 9578	8.2	6.8	G1V	1.00	78	1
HD 10180	7.3	5.9	G1V	0.84	95	0
HD 13808	8.4	6.3	K2V	0.72	88	0
HD 20003	8.4	6.6	G8V	0.69	78	0
HD 25171	7.8	6.5	F8V	0.79	82	0
HD 27631	8.2	6.6	G3V	0.91	83	1
HD 31253	7.1	5.8	F8V	0.62	97	0
HD 31527	7.5	6.0	G0V	0.75	94	0
HD 38283	6.7	5.3	G0V	0.78	87	0
HD 39194	8.1	6.1	K0V	1.02	89	4
HD 51608	8.2	6.3	K0V	0.68	86	0
HD 86226	7.9	6.5	G2V	0.53	83	0
HD 86264	7.4	6.2	F7V	0.84	87	0
HD 90156	6.9	5.2	G5V	0.53	89	0
HD 93385	7.5	6.1	G2V	0.94	92	0
HD 96167	8.1	6.6	G5IV	0.58	81	1
HD 96700	6.5	5.0	G0V	0.49	88	0
HD 100777	8.4	6.7	K0V	0.42	77	0
HD 126525	7.9	6.2	G4V	0.90	85	1
HD 134060	6.3	4.8	G0V	1.01	84	5
HD 142245	7.5	5.1	K0IV	0.96	91	1
HD 148156	7.7	6.4	FV8	0.95	82	5
HD 154088	6.6	4.8	K0V	0.94	95	4
HD 157172	7.9	6.1	G9V	1.09	85	5
HD 158038	7.5	5.2	K2IV	0.93	89	0
HD 164604	9.8	7.2	K2V	1.01	72	6
HD 181342	7.6	5.3	K0IV	1.16	88	1
HD 212771	7.6	5.5	G8IV	1.04	87	0
HD 215152	8.1	5.8	K3V	0.72	98	0
HD 215497	9.0	6.8	K3V	0.73	75	0
HD 220689	7.8	6.3	G3V	0.88	78	0
HD 220773	7.1	5.7	G0V	0.86	85	0

All target were observed in the *Ks*-band in a first imaging epoch using the NACO S13 optics (pixel scale of about 13 mas pixel^{-1}). We always used the dichroic VIS to split the beam of light coming from the telescope to the IR detector and the visible wavefront sensor of NACO, which was always used in combination with its 14 × 14 lens-let array for the wavefront sensing. For each target 11 images (each the average of 120 short detector integrations with detectorintegrationtime, DIT = 0.5 s) were taken in the jitter-mode with a jitter-width of 7 arcsec, sufficiently large to well sample the infrared sky-background and to avoid overlapping of the point spread function (PSF) of the bright exoplanet host stars at the individual jitter-positions. The choice of the short DIT, as well as of the used optics, limits saturation effects only on the few central pixel of the PSF of the observed bright exoplanet host stars. Hence, close companions of our targets are detectable down to the diffraction limit of the 8.2 m VLT. Internal lamp flats, as well as skyflats were used to calibrate the individual pixel sensitivity of the NACO infrared detector. The background estimation and subtraction, as well as the flat-fielding of all images, was achieved with the ESO package ECLIPSE[1] (Devillard 2001), which finally also combined all images, using a shift+add procedure.

By comparing NACO images, taken at two different observing epochs, (sub)stellar companions of the observed exoplanet host stars can be identified as objects, which share a common proper motion with our targets. Due to the small pixel scale of the NACO S13 optics an astrometric precision on the milliarcsec(mas)-level

[1] ESO C Library for an Image Processing Software Environment

Table 2. The astrometric calibration of all NACO observing runs, whose data are presented in this paper. The determined pixel scale PS and the detector position angle DPA are listed with their uncertainties.

optics	epoch	*PS* (mas pixel^{-1})	*DPA* (°)
NACO S13	2012/08	13.231 ± 0.030	0.61 ± 0.15
NACO S13	2013/01	13.213 ± 0.040	0.83 ± 0.10
NACO S13	2013/07	13.218 ± 0.034	0.68 ± 0.10

is achievable, sufficiently small to identify comoving companions of our targets already after several months of epoch difference, in particular as the average proper motion of our targets is about 170 mas yr^{-1}. In order to achieve accurate astrometric measurements all our NACO observations were astrometrically calibrated. Therefore, in each observing run we took images of the globular cluster 47 Tuc, for which precise *Hubble Space Telescope* astrometry is available for several of its members. The pixel scale PS and the position angle DPA of the NACO S13 optics, obtained for all observing runs, whose data are presented in this paper, are summarized in Table 2.

In order to determine the apparent photometry of detected comoving companions, photometric standard stars from the list of Persson et al. (1998) were observed in all observing runs with the same set-up, which was used for the high-contrast imaging of our targets. The standard star observations were reduced in the same way, as described above for the observed targets, and we used aperture photometry to measure the apparent magnitudes of the standard stars and the detected companions. Thereby, the PSFs of the bright exoplanet host stars, which contaminate the photometric measurements of the close companions, were always removed by the roll-subtraction-technique, described recently by Ginski et al. (2014).

The first epoch NACO observations of our targets were taken end of 2012 August and in 2013 January, and 33 exoplanet host stars could be observed in total. Companion-candidates were identified among 12 targets (see Table 1), for which second epoch follow-up imaging was carried out in 2013 July, using the same set-up as for the first epoch observations.

By comparing our first and second epoch NACO images we found that all the companion candidates, imaged close to the stars HD 27631, HD 39194, HD 126525, HD 134060, HD 148156, HD 154088, HD 157172, HD 164604, and HD 181342 are only non-moving sources, which are clearly unrelated to the exoplanet host stars and are located most probably far beyond the stars in the background (see as example the NACO astrometry of the detected companion candidates of the exoplanet host star HD 154088, which is shown in Fig. A1).

In contrast, we could detect three new comoving companions close to the exoplanet host stars HD 9578, HD 96167, and HD 142245, whose observations will be described in detail in the following subsections.

2.1 HD 9578

The exoplanet host star HD 9578 is a G1 dwarf with a mass of about 1.1 $M_\odot$ (Santos et al. 2013) and an age of approximately 6 Gyr, as determined by Feltzing, Holmberg & Hurley (2001), Marsakov & Shevelev (1995), and Holmberg, Nordström & Andersen (2009). The star is located at a distance of about 57 pc

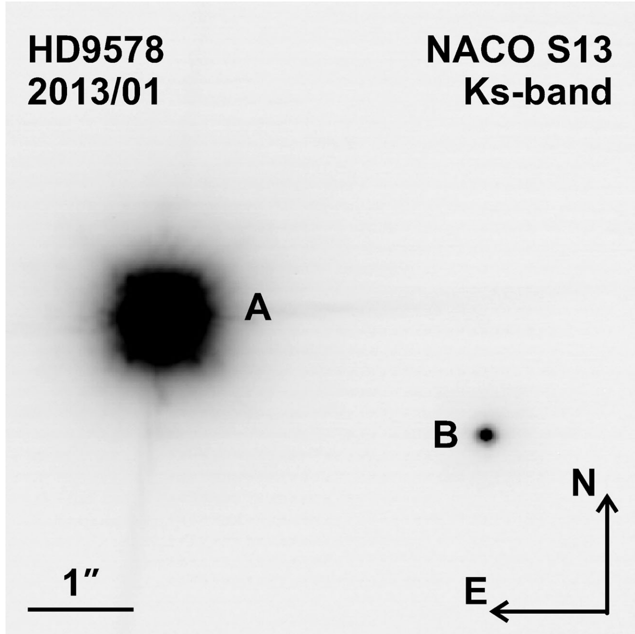

Figure 1. The first epoch NACO image of the exoplanet host star HD 9578 with its comoving companion HD 9578 B, taken by us with NACO in the *Ks*-band on 2013 January 24. The companion is clearly detected in this images about 3.2 arscec (or 186 au of projected separation) south-west of the exoplanet host star.

(π = 17.44 ± 0.85 mas) in the constellation Sculptor and exhibits a proper motion of $\mu_{\rm RA} = -30.95 \pm 0.69$ mas yr^{-1} and $\mu_{\rm Dec} = -38.41 \pm 0.54$ mas yr^{-1}, as measured by the ESA astrometry satellite *Hipparcos* (see van Leeuwen 2007). HD 9578 harbours an exoplanet with a minimum mass of $m\sin(i) = 0.62\,M_{\rm Jup}$, which revolves around its parent star on a slightly eccentric orbit ($e = 0.19$) with a semimajor axis of $a = 1.26$ au (orbital period of about 494 d), as reported by Udry (2009).

We observed HD 9578 the first time on 2013 January 24 with NACO in the *Ks*-band. A faint companion candidate was detected about 3.2 arcsec (or 186 au of projected separation) south-west of the exoplanet host star. Our fully reduced first epoch NACO image of HD 9578 with its close companion candidate is shown in Fig. 1. In order to confirm the companionship of this candidate with astrometry we carried out second epoch follow-up imaging observations with NACO on 2013 July 25.

We measured the relative astrometry (angular separation and position angle) of the companion candidate to HD 9578 after subtraction of the PSF of the bright exoplanet host star via the roll-subtraction-technique. The determined astrometry of the candidate for both NACO observing epochs is summarized in Table 3. Using the well-known proper and parallactic motion of HD 9578 we could derive how much the relative astrometry of the detected companion candidate should have changed within the given epoch difference in the case that the candidate is just a non-moving background source. The expected values for angular separation and position angle are also listed in Table 3 and are illustrated in Fig. 2 for a range of time.

While the angular separation and the position angle of the companion candidate to the exoplanet host star do not change significantly between both observing epochs, we expect an increase of the position angle, in the case that the candidate is a non-moving background source. Our NACO astrometry rejects this background hypothesis for the companion candidate with a significance of more

Table 3. The angular separations (sep) and position angles (PA) of all detected comoving companions relative to their parent stars, as measured in our NACO, and for HD 96167 B also in the 2MASS images. In the columns sep_{bg} and PA_{bg}, we show the expected values of both quantities in the case that the detected companions would be non-moving background objects. The significance level on which this background hypothesis can be rejected for all companions, is listed separately for sep and PA in the column s_{bg}.

companion	epoch	*sep* (arcsec)	*PA* (°)	sep_{bg} (arcsec)	PA_{bg} (°)	s_{bg} (σ)
HD 9578 B	NACO S13 2013/01/24	3.245 ± 0.010	251.19 ± 0.10	–	–	–
	NACO S13 2013/07/25	3.244 ± 0.008	251.07 ± 0.10	3.257 ± 0.010	251.53 ± 0.11	$1.0 + 3.1$
HD 96167 B	2MASS 2001/01/16	5.766 ± 0.101	296.82 ± 0.88	–	–	–
	NACO S13 2013/01/24	5.873 ± 0.018	297.06 ± 0.10	5.285 ± 0.102	300.63 ± 0.89	$5.7 + 4.0$
HD 142245 BC	NACO S13 2012/08/31	2.498 ± 0.006	169.15 ± 0.16	–	–	–
	NACO S13 2013/07/24	2.494 ± 0.006	169.07 ± 0.10	2.493 ± 0.006	167.99 ± 0.16	$0.1 + 5.7$

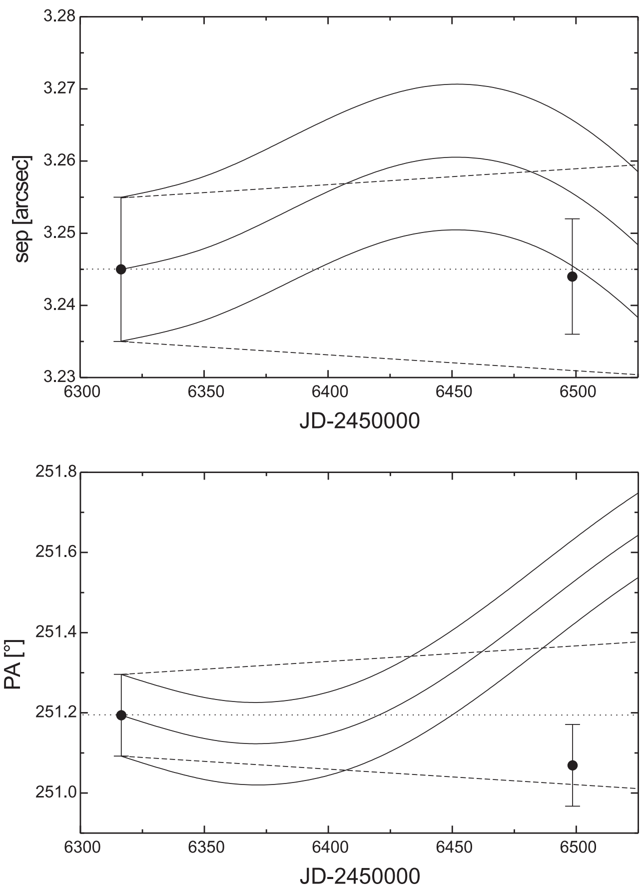

Figure 2. The angular separation and position angle of the detected companion candidate of HD 9578 for both NACO observing epochs. The wobbled lines illustrate the expected change of both quantities in the case that the candidate is a non-moving background object. The dashed straight lines show the expected maximal change of separation and position angle for an object on a circular orbit around HD 9578.

than 3σ. Hence, we conclude that the detected candidate is a real comoving companion of the exoplanet host star, which will be named as HD 9578 B from here on.

The apparent *Ks*-band photometry of HD 9578 B, as measured in our two NACO observing epochs, is summarized in Table 4. With the given distance of the exoplanet host star we also derived the absolute magnitude of the detected companion, which is also listed in this table.

Table 4. The apparent *Ks*-band photometry of all detected comoving companions, as measured in our NACO images. The absolute magnitudes of the companions are derived from their averaged apparent photometry and the well-known distances of the exoplanet host stars.

companion	epoch	*Ks* (mag)	M_{Ks} (mag)
HD 9578 B	2013/01	11.50 ± 0.04	7.67 ± 0.11
	2013/07	11.42 ± 0.05	
HD 96167 B	2013/01	12.17 ± 0.05	7.47 ± 0.18
HD 142245 BC	2012/08	9.89 ± 0.05	4.64 ± 0.16
	2013/07	9.79 ± 0.04	

2.2 HD 96167

HD 96167 is G5 sub-giant star, with a mass of about 1.3 $M_\odot$ and an age of ∼4 Gyr, which is located in the constellation Crater at a distance of approximately 87 pc, as described by Peek et al. (2009). The same team reported on the detection of an exoplanet in orbit around this star, which exhibits a minimum mass of $m\sin(i) = 0.68 \pm 0.18\,M_{\rm Jup}$ and revolves around its parent star on an eccentric orbit ($e \sim 0.7$) with an orbital period of about 499 d (semimajor axis of ∼1.3 au). The parallactic and proper motion of HD 96167 are both well known from *Hipparcos* measurements ($\pi = 11.5 \pm 0.89$ mas, $\mu_{\rm RA} = -49.69 \pm 0.83$ mas yr^{-1}, and $\mu_{\rm Dec} = -7.55 \pm 0.80$ mas yr^{-1}, see van Leeuwen 2007).

We observed HD 96167 in one observing epoch with NACO on 2013 January 24. Our fully reduced NACO image of HD 96167 is shown in Fig. 3.

Beside the bright exoplanet host star, which is located in the centre of the NACO image, a fainter companion candidate is detected about 5.8 arcsec (506 au of projected separation) north-west of the star. This companion is also detected in the 2MASS images of HD 96167 taken on January 16th 2001 in the *J*, *H*, and *Ks*-bands.

The individual 2MASS images are astrometrically calibrated with all stars (except the exoplanet host star HD 96167) detected in these images, whose positions are listed in the 2MASS Point Source Catalogue (2MASS-PSC, see Skrutskie et al. 2006), which are not contaminated by nearby sources, and exhibit a triple A photometry quality flag. We obtain a pixel scale of PS = 1000.06 ± 0.34 mas pixel^{-1} and a detector position angle of DPA = $-0.01 \pm 0\overset{\circ}{.}02$. In order to determine the relative astrometry and photometry of the candidate, we deconvolved the 2MASS images using the Richardson–Lucy algorithm (Richardson 1972; Lucy 1974). Thereby, we used the average of point sources, detected around the

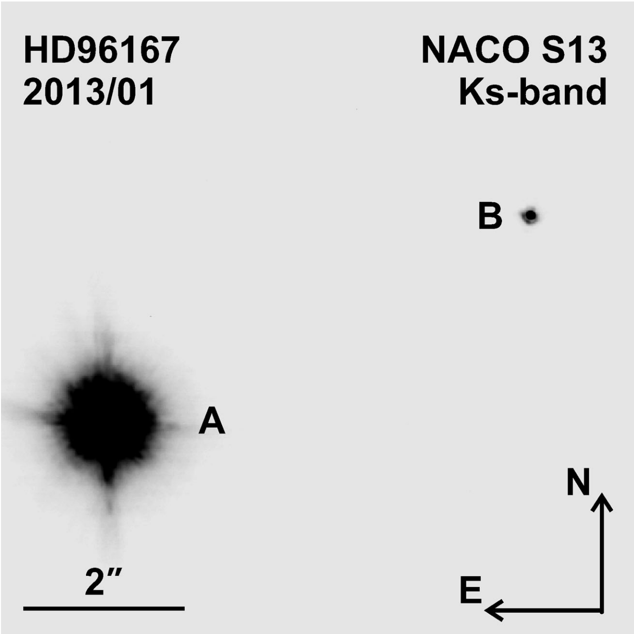

Figure 3. The NACO *Ks*-band image of the exoplanet host star HD 96167 with its comoving companion HD 96167 B, taken on 2013 January 24. The companion is clearly detected in the image about 5.8 arcsec (or 506 au of projected separation) north-west of the exoplanet host star, and could also be detected by 2MASS, whose processed images are shown in Fig. 4.

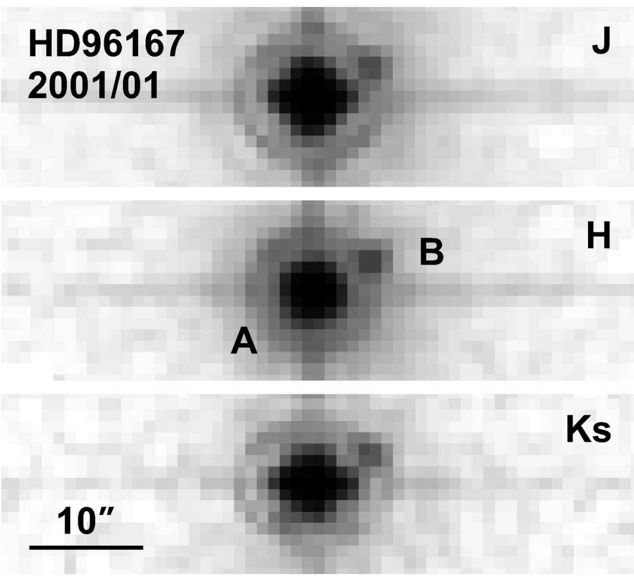

Figure 4. The deconvolved 2MASS *J*-, *H*-, and *Ks*-band images of the exoplanet host star HD 96167 with its comoving companion HD 96167 B, which is located about 5.8 arcsec north-west of the star. The 2MASS images were taken on 2001 January 16. North is up and East to the left.

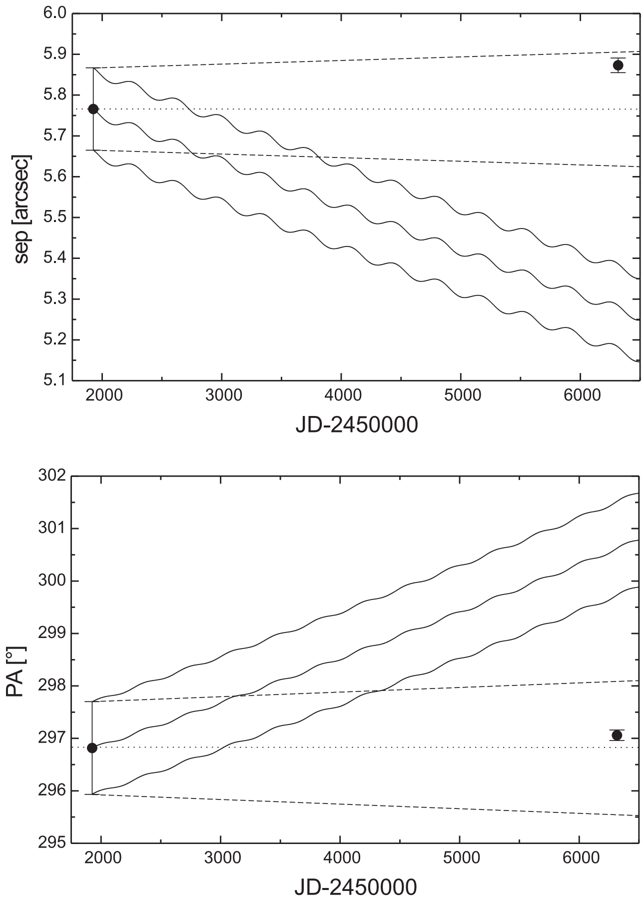

Figure 5. The angular separation and position angle of the detected companion candidate of HD 96167 for the 2MASS and our NACO observing epoch. The wobbled lines illustrate the expected change of separation and position angle in the case that the candidate is a non-moving background source. The dashed straight lines show the expected maximal change of both parameters for an object on a circular orbit around HD 96167.

exoplanet host star in the 2MASS images, as PSF reference. The deconvolved 2MASS images are shown in Fig. 4.

The astrometry of the companion, as measured in the 2MASS images, as well as in our NACO image, is listed in Table 3 and is illustrated in Fig. 5.

The separation and position angle of the candidate to HD 96167 do not significantly change within the 12 yr of epoch difference, while a change of both quantities is expected in the case that the candidate is a non-moving background source. We can reject this background hypothesis for the companion candidate on a significance level of more than 5σ. Hence, the companionship of the detected candidate, which will be named as HD 96167 B from here on, is confirmed via astrometry.

The apparent *Ks*-band magnitude of HD 96167 B, as measured in our NACO image, is listed in Table 4, together with the absolute *Ks*-band magnitude of the companion, as derived from its apparent infrared photometry and the well-known distance of the exoplanet host star. In addition, we also determined the apparent photometry of HD 96167 B in the 2MASS images, using aperture photometry after PSF subtraction via the roll-subtraction-technique. Thereby, stars are used as photometric references, which are detected in the 2MASS images close to the exoplanet host star, and exhibit well-known magnitudes, which are listed in the 2MASS-PSC. We obtained $J = 13.12 \pm 0.27$ mag, $H = 12.64 \pm 0.20$ mag, and $Ks = 12.15 \pm 0.19$ mag for HD 96167 B, which also yields the absolute magnitudes of the companion of $M_J = 8.42 \pm 0.25$ mag, $M_H = 7.94 \pm 0.26$ mag, and $M_{Ks} = 7.45 \pm 0.25$ mag. The determined 2MASS photometry of HD 96167 B agrees well with the NACO photometry of the companion in the *Ks*-band.

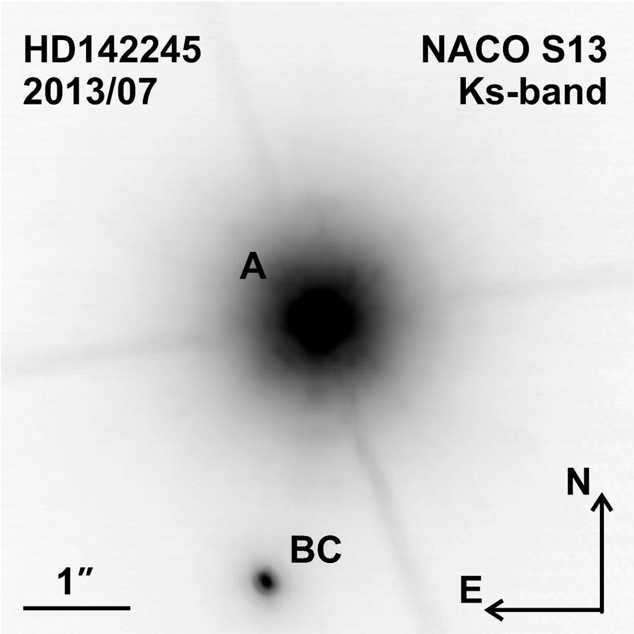

Figure 6. The second epoch NACO image of the exoplanet host star HD 142245 with its comoving companion, which is clearly detected about 2.5 arcsec (or 274 au of projected separation) south of HD 142245. The image was taken on 2013 July 24 in the *Ks*-band. An enlarged detail of the companion for both NACO observing epochs is shown in Fig. 8.

2.3 HD 142245

The star HD 142245 is K0 sub-giant with a mass of about 1.7 $M_\odot$, a radius of around 5 $R_\odot$, and an age of approximately 2.3 Gyr (see Johnson et al. 2011), which is located at a distance of about 110 pc ($\pi = 9.13 \pm 0.62$ mas, see van Leeuwen 2007) in the constellation Serpens. Johnson et al. (2011) detected an exoplanet with a minimum mass of $1.9 \pm 0.2\,M_{\rm Jup}$, which revolves around HD 142245 on an eccentric orbit ($e < 0.32$) with a semimajor axis of about 2.8 au and an orbital period of more than thousand days.

HD 142245 was observed with NACO by us in first epoch on 2012 August 31 and a companion candidate was detected, which is located about 2.5 arcsec (273 au of projected separation) south of the star. The second epoch follow-up imaging observations of the exoplanet host star were taken on 2013 July 24. Our fully reduced second epoch NACO image of HD 142245 is shown in Fig. 6.

The angular separation and the position angle of the detected companion candidate to HD 142245, as measured in both NACO observing epochs, is listen in Table 3 and is illustrated in Fig. 7.

Both quantities do not change significantly within the given epoch difference, while we expect that in particular the position angle of the candidate should decrease in the case that this object is a non-moving background source, as been calculated with the well-known parallactic and proper motion of the exoplanet host star ($\mu_{\rm RA} = -55.58 \pm 0.74$ mas yr^{-1}, and $\mu_{\rm Dec} = -20.82 \pm 0.63$ mas yr^{-1}; van Leeuwen 2007). The background hypothesis for the candidate can be rejected with a significance of more than 5σ. Hence, the detected candidate can be considered as a real comoving companion of HD 142245. The apparent *Ks*-band magnitudes of the new companion, as measured in both NACO imaging epochs, as well as its derived absolute *Ks*-band photometry are summarized in Table 4.

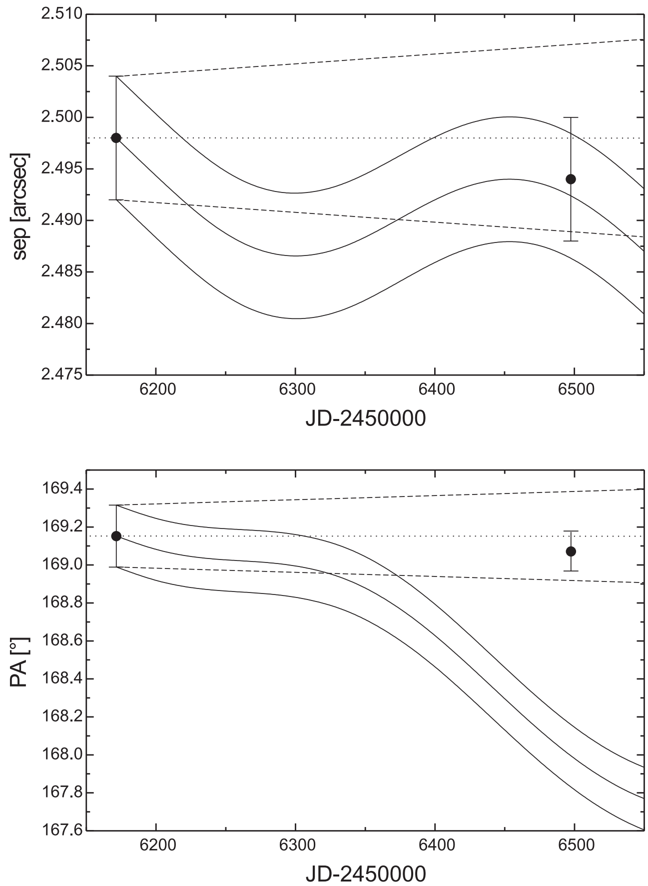

Figure 7. The angular separation and position angle of the detected companion candidate of HD 142245 for both NACO observing epochs. The wobbled lines illustrate the expected change of separation and position angle in the case that the candidate is a non-moving background object. The dashed straight lines show the expected maximal change of both parameters for an object on a circular orbit around HD 142245.

Table 5. Projected separations, derived masses, and SpTs of the detected comoving companions of exoplanet host stars.

companion	proj. sep. (au)	mass ($M_\odot$)	SpT
HD 9578 B	186	0.21	M4
HD 96167 B	506	0.23	M4
HD 142245 B & C	273	0.56	M1

3 DISCUSSION AND SUMMARY

With NACO we found new comoving companions close to the exoplanet host stars HD 9578, HD 96167, and HD 142245. We determined the masses and spectral types (SpT) of all these companions, which are summarized in Table 5. The masses of the companions were derived with their absolute magnitudes, using the evolutionary models for low-mass stars from Baraffe et al. (1998), by assuming an age of 5 Gyr, which is the average age of the observed exoplanet host stars. The SpTs of the companions were estimated from their absolute magnitudes, using the magnitude–SpT relation from Reid et al. (2004).

According to its infrared photometry, we expect that the companion of HD 9578 is a mid-M dwarf (SpT of M4) with a mass of about 0.2 $M_{\odot}$, which orbits its primary on an orbit with a projected separation of about 190 au. Tokovinin & Lépine (2012) reported that HD 9578 exhibits also a very wide companion candidate, which is located south (PA = 185°.67 ± 0°.01) of the star at an angular separation of 892.98 ± 0.17 arcsec (or about 51200 au of projected separation) at the 2MASS observing epoch in 1998. We checked the proper motion of the candidate, which is listed in the UCAC4 catalogue ($\mu_{RA} = -34.2 \pm 1.3$ mas yr^{-1}, and $\mu_{Dec} = -30.2 \pm 0.9$ mas yr^{-1}; see Zacharias et al. 2013). Compared to the proper motion of the exoplanet host star, which is well known from *Hipparcos* measurements, this yields a relative motion between the candidate and HD 9578 of 8.8 ± 1.1 mas yr^{-1}, or 0.51 ± 0.07 au yr^{-1} of projected relative motion at the distance of the star. In contrast, the escape velocity for an object on a 51200 au orbit around HD 9578 is expected to be only 0.04 au yr^{-1}, hence significantly smaller than the measured relative motion between the wide companion candidate and the exoplanet host star. Furthermore, the apparent infrared magnitudes of the candidate ($J = 9.858 \pm 0.026$ mag, $H = 9.361 \pm 0.023$ mag, $Ks = 9.288 \pm 0.019$ mag, see the 2MASS-PSC), are about 1.5 mag fainter than those expected for a main-sequence star, which is located at the well-known distance of HD 9578 of about 57 pc. Therefore, we can clearly rule out the companionship of this wide candidate by both astrometry and photometry.

The detected comoving companion of HD 96167 exhibits a projected separation to its primary of about 500 au. From our NACO and the 2MASS photometry of the companion, we expect that it is a low-mass (~0.2 $M_{\odot}$) mid-M dwarf with a SpT of M4.

The photometry of the comoving companion of HD 142245, which is located at a projected separation of about 270 au to its primary, is consistent with a M0 dwarf with a mass of 0.69 $M_{\odot}$. Fig. 8 shows the enlarged detail of this companion, as detected in our two NACO images, together with contour lines. While the image of the exoplanet host star appears radial symmetric in both NACO images, the comoving companion exhibits an elongated image, whose apse-line is orientated approximately in the north to south direction in the first NACO image, while it is orientated in the north-east to south-west direction in the second epoch NACO observation.

The elongation of the companion might indicate that it is actually a very close binary system itself, whose components are separated by less than the diffraction limit of the 8.2 m VLT in the *Ks*-band, i.e. both objects should exhibit an angular separation to each other, which is smaller than about 70 mas.

If we assume that the companion is indeed a close binary, composed of two equally bright stars, we can derive the masses and SpTs of its components. Our NACO photometry of the companion is consistent with two early-type M dwarfs with a SpT of M1, and a mass of 0.56 $M_{\odot}$.

In order to approximate the angular separation of the two components to each other, we modelled images of close binaries by adding PSFs with angular separations up to 80 mas, i.e. up to separations, which are already larger than the diffraction limit of the 8.2 m VLT in the *Ks*-band. As PSF of the individual components we used either a PSF-model calculated for NACO's S13 optics in the *Ks*-band, or an average PSF composed of the images of non-saturated bright sources, imaged with NACO in both observing runs. We compared the images of the obtained binary models with our NACO images of the comoving companion, by measuring their first- and second-order moments. Both PSF approaches yielded similar results and we derived a binary separation of 29 ± 5 mas in the first and

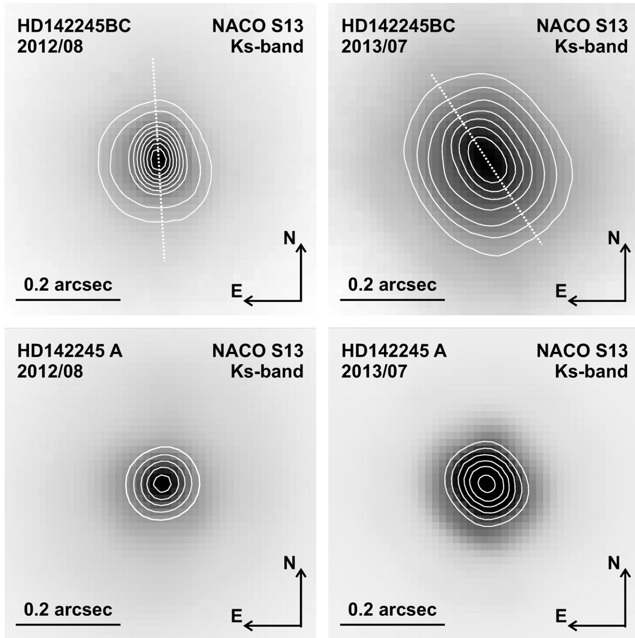

Figure 8. The enlarged detail of the comoving companion of the exoplanet host star HD 142245 (top panels), imaged in our 1st and 2nd epoch with NACO in the *Ks*-band on 2012 August 31 and on 2013 July 24. In both observing epochs the companion exhibits an elongated image, which indicates that it might be a close binary system, i.e. HD 142245 could be actually a hierarchical triple stellar system, which hosts an exoplanet. Contour lines are shown as solid lines. The orientation of apse-line of the elliptical image of the companion is illustrated with dotted lines. The enlarged detail of the exoplanet host star is shown for comparison in the bottom panels for both observing epochs.

50 ± 12 mas in the second NACO imaging epoch, respectively. In addition, we also determined the position angle of the semi-major axis of the elliptical image of the comoving companion of HD 142245 in both NACO observing epochs, using the first and second-order moments, which were measured in the NACO images at the position of the companion after subtraction of the PSF of the bright exoplanet host star. The position angle of the elongated image of the companion significantly increases from PA = 3° ± 2° to PA = 33° ± 3° within the given epoch difference of 327 d between our two NACO observations.

The derived average angular separation of the close binary is 39.5 ± 6 mas, which corresponds to a projected separation of only 4.3 ± 0.7 au at the distance of the exoplanet host star. This yields an estimate of the orbital period of the close binary of $P = 8.5 \pm 2$ yr, assuming a total system mass of 1.12 $M_{\odot}$, as derived above. Hence, the expected maximal change of angular separation and position angle for a gravitationally bound orbit is $\mathrm{dsep}/\mathrm{d}t = 29 \pm 9$ mas yr^{-1}, obtained for an edge-on, and $\mathrm{dPA}/\mathrm{d}t = 42° \pm 11°$ yr^{-1} for a face-on orbit, respectively. Within the given epoch difference we find $\mathrm{dsep}/\mathrm{d}t = 23 \pm 15$ mas yr^{-1} and $\mathrm{dPA}/\mathrm{d}t = 34° \pm 4°$ yr^{-1}, i.e. the detected change of the relative astrometry of the close binary is well consistent with orbital motion, which is expected for such a close gravitationally bound stellar system. Hence, we conclude that the comoving companion of HD 142245 is most probably a close binary system, and we name its two potential components as HD 142245 B, and HD 142245 C, respectively.

We rule out that the elongation of the image of the companion of HD 142245 is an AO distortion, as it is observed only for this

Table 6. The currently known exoplanet host triple stellar systems and the potential triple system HD 142245. The systems are sorted by their projected extent, derived with the measured angular separations between the components of the systems, and the known distances of the exoplanet host stars. The configuration of the systems is given with the exoplanet host star listed always at first.

system name	configuration	projected extent (au)[a]
HD 19994	A+BC	52
GJ 667	C+AB	227
WASP-12	A+BC	241
HD 65216	A+BC	256
HAT-P-8	A+BC	267
HD 142245	A+BC	273
HD 132563	B+AC	365
HD 196050	A+BC	511
Kepler-13	A+BC	610
HD 178911	B+AC	794
16 Cyg	B+AC	860
30 Ari	B+AC	1517
HD 219449	A+BC	2283
HD 126614	AB+C	3043
HD 40979	A+BC	6395
α Cen	BA+C	10133

[a]See Roell et al. (2012) and references therein, Ginski et al. (2013), Bechter et al. (2014), and Shporer et al. (2014). The projected extent of α Cen is derived with the 2MASS astrometry of the system from observing epoch 2000.

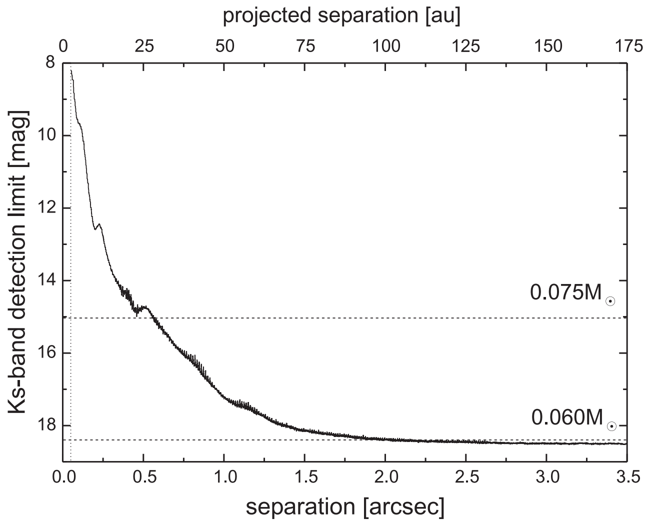

Figure 9. The achieved average (S/N = 3) detection limit of our NACO imaging survey in the *Ks*-band, for a range of angular (bottom) and projected (top) separation to the observed exoplanet host stars. A limiting magnitude of about 18.5 mag is reached in the background limited region at angular separations beyond about 2 arcsec (or ∼100 au of projected separation). The vertical dotted line shows the saturated area on the NACO detector, which is located close to the bright exoplanet host stars at angular separations smaller than about 50 mas (or ∼2.5 au of projected separation), which is located already within the *Ks*-band diffraction limit of the VLT. The dashed horizontal lines shows the expected apparent *Ks*-band magnitudes of companions with 60 and 75 $M_{\rm Jup}$, as given by the Baraffe et al. (2003) models, respectively. The magnitudes are derived for the average distance of our targets of about 50 pc and their average age of 5 Gyr.

companion and in both observing epochs, while all other sources detected in our survey in all epochs, even those with larger angular separations to the AO reference sources, appear radial symmetric (as it is illustrated for the image of the exoplanet host star HD 142245 for both observing epochs in Fig. 8). Furthermore, the apse-line of the elliptical image of the companion of HD 142245 is not directed towards the AO reference, which is expected in the case that the elongation of the image would be an AO distortion.

The HD 142245 system could be a new member in the slowly growing list of known triple stellar systems, which harbour exoplanets. Up to now, in total only 16 of these systems are known, which are summarized in Table 6. Most of these systems are composed like HD 142245, i.e. in these systems the exoplanet host star is also the most massive primary component, which orbits together with a close binary companion at a wider separation around the barycenter. Only two systems are presently known, in which the detected exoplanets reside within the close binary, and orbit the primary or secondary component of the system, which exhibits an additional wide companion.

Among all 33 exoplanet host stars, which were observed in the course of our high-contrast imaging survey, new comoving companions could be detected around three of our targets, yielding a detection rate of about 9 per cent. According to Roell et al. (2012) or Mugrauer, Ginski & Seeliger (2014), the multiplicity rate of exoplanet host stars is about 12–13 per cent. Hence, for 33 observed exoplanet host stars we expect to detect 4 ± 2 companions, which complies well with the number of comoving companions, detected in our survey.

Additional companions of the observed exoplanet host stars can be ruled out on the basis of the detection limits, achieved in our NACO observations. The average (S/N = 3) detection limit, determined for all our NACO images, is illustrated in Fig. 9. The individual detection limits for all observed targets are summarized in Table 7.

The observed bright exoplanet host stars only saturate the NACO detector on the few central pixels of the stellar PSF at angular separations smaller than about 50 mas (or ∼2.5 au of projected separation) in average, which already resides within the diffraction limit of the 8.2 m VLT in the *Ks*-band. Hence, all sufficiently bright companions of the observed stars can be detected at angular separations, which range from the VLT diffraction limit up to the border of the fields of view of our NACO images. As the jitter-technique is applied the total covered field of view is larger than the field of view of the NACO S13 optics. In average companions with angular separations up to about 7.5 arcsec (or ∼370 au of projected separation) are detectable around our targets.

In the background limited region, at angular separations larger than about 2 arcsec (or ∼100 au of projected separation) from the observed bright exoplanet host stars, companions as faint as Ks = 18.5 mag are detectable in average in our NACO images. The limiting magnitude reached in this region allows the detection of companions with masses down to about 60 $M_{\rm Jup}$, as derived with the well-known distances of our targets (50 pc in average), and the Baraffe et al. (2003) evolutionary models, using the average age of our targets of about 5 Gyr. All stellar companions, i.e objects with masses larger than 75 $M_{\rm Jup}$, are detectable at angular separations beyond ∼0.6 arcsec (or about 30 au of projected separation). Hence, our NACO imaging survey, well complements the results of our ongoing lucky- and seeing-limited imaging searches for wide companions of exoplanet host stars, which

Table 7. The achieved detection limits with NACO in the *Ks*-band for all exoplanet host stars, which were observed in the course of our imaging survey. We list the achieved (S/N = 3) detection limits in the background limited regions around our targets, as well as the minimum masses of detectable companions, derived with the distances of the exoplanet host stars and the Baraffe et al. (2003) evolutionary models for the average age of our targets of 5 Gyr. At the outer edge of field of view, the detection limit decreases up to 0.5 mag due to the used jitter-technique, which results in an increase of the minimum mass of detectable companions in this outer region of about 3 $M_{\rm Jup}$, in average. In the last column we list the range of projected separation in which all stellar companions of the observed stars can be detected in our NACO images. The averaged (S/N = 3) detection limit of our NACO imaging survey, dependent on the angular separation to the bright exoplanet host stars, is illustrated in Fig. 9.

star	limit (mag)	limit ($M_{\rm Jup}$)	proj. sep (au)
HD 8535	18.8	60	23–431
HD 9578	17.8	67	39–394
HD 10180	19.4	49	13–324
HD 13808	19.3	46	8–237
HD 20003	18.3	60	18–378
HD 25171	18.6	61	26–436
HD 27631	16.6	70	40–305
HD 31253	20.3	47	15–362
HD 31527	19.6	48	12–318
HD 38283	20.6	42	11–321
HD 39194	16.8	63	17–167
HD 51608	19.0	51	10–271
HD 86226	19.3	53	12–387
HD 86264	19.3	60	30–551
HD 90156	20.3	37	5–177
HD 93385	19.6	50	12–352
HD 96167	18.8	66	51–740
HD 96700	20.6	37	7–209
HD 100777	18.6	60	18–369
HD 126525	14.9	74	65–255
HD 134060	15.7	68	22–163
HD 142245	15.9	82	–[3]
HD 148156	16.9	70	49–345
HD 154088	18.4	46	8–119
HD 157172	16.3	68	21–276
HD 158038	17.9	73	132–680
HD 164604	18.4	59	13–340
HD 181342	18.7	70	138–762
HD 212771	19.0	70	159–806
HD 215152	19.6	41	6–145
HD 215497	18.2	61	26–300
HD 220689	17.9	63	26–305
HD 220773	18.8	60	31–337

[3]No range of separation is given for this target, as the achieved limiting magnitude for this exoplanet host star allows the detection of companions with mass down to 82 $M_{\rm Jup}$ at projected separations between about 220 and 670 au. All stellar companions of this star with masses larger than 0.1 $M_\odot$ can be detected beyond about 160 au of projected separation.

exhibit larger fields of view but reach lower contrast. Once all of these imaging surveys are done, their results will complete our knowledge of the stellar multiplicity of the exoplanet host stars.

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APPENDIX A

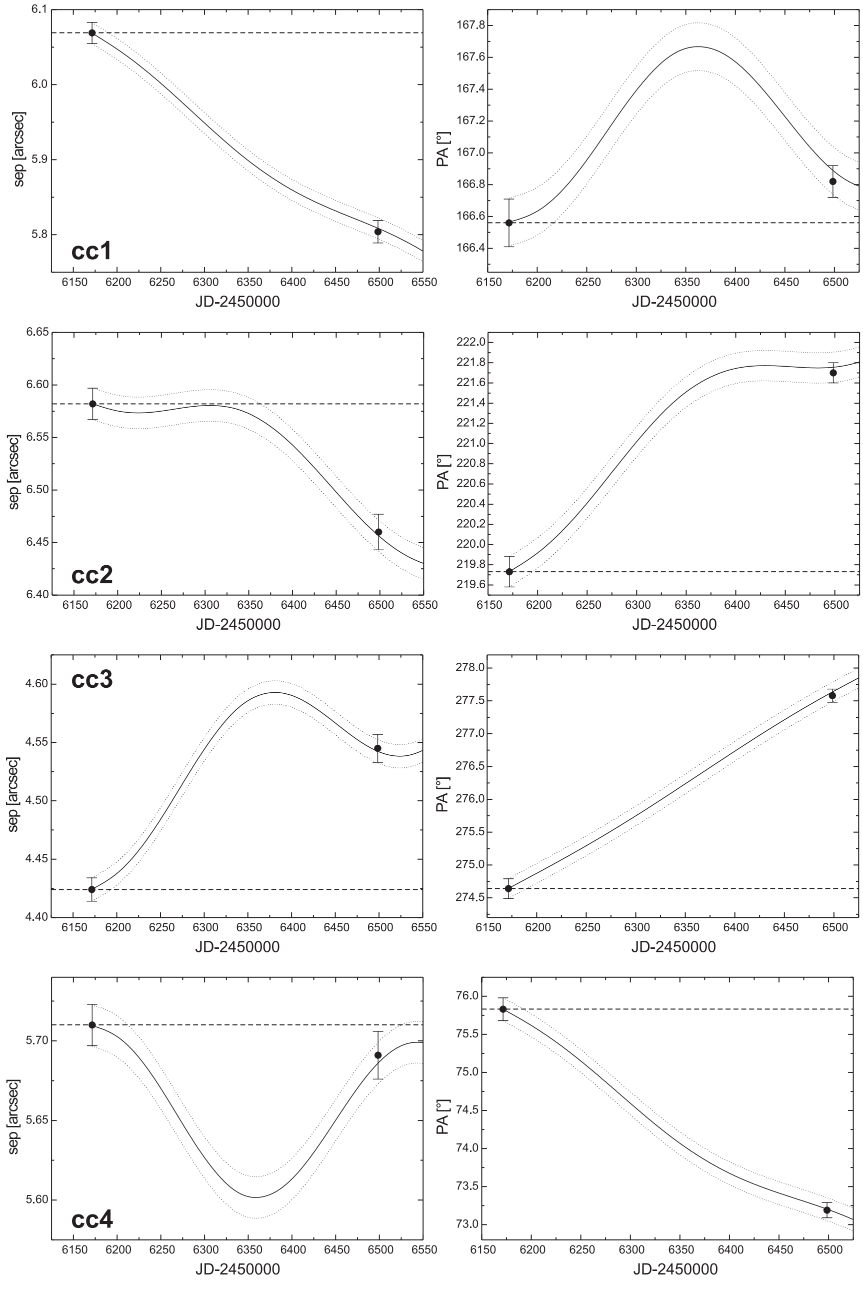

Figure A1. The angular separations and position angles of all companion candidates detected around HD 154088 for both NACO observing epochs. The wobbled lines illustrate the expected change of both quantities in the case that the candidates are non-moving background sources, derived with the well-known proper and parallactic motion of the star, as measured by *Hipparcos*. The NACO astrometry of all candidates agrees very well with the background hypothesis, i.e. the detected companion candidates are non-moving sources, which are unrelated to the exoplanet host star and are located most probably far beyond the star in the background.

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