

# Searching for gas giant planets on Solar system scales – a NACO/APP $L'$ -band survey of A- and F-type main-sequence stars

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Accepted 2015 August 3. Received 2015 July 2; in original form 2015 March 17

## ABSTRACT

We report the results of a direct imaging survey of A- and F-type main-sequence stars searching for giant planets. A/F stars are often the targets of surveys, as they are thought to have more massive giant planets relative to solar-type stars. However, most imaging is only sensitive to orbital separations  $>30$  au, where it has been demonstrated that giant planets are rare. In this survey, we take advantage of the high-contrast capabilities of the Apodizing Phase Plate coronagraph on NACO at the Very Large Telescope. Combined with optimized principal component analysis post-processing, we are sensitive to planetary-mass companions ( $2\text{--}12 M_{\text{Jup}}$ ) at Solar system scales ( $\leq 30$  au). We obtained data on 13 stars in the  $L'$  band and detected one new companion as part of this survey: an  $M6.0 \pm 0.5$  dwarf companion around HD 984. We re-detect low-mass companions around HD 12894 and HD 20385, both reported shortly after the completion of this survey. We use Monte Carlo simulations to determine new constraints on the low-mass ( $<80 M_{\text{Jup}}$ ) companion frequency, as a function of mass and separation. Assuming solar-type planet mass and separation distributions, normalized to the planet frequency appropriate for A-stars, and the observed companion mass-ratio distribution for stellar companions extrapolated to planetary masses, we derive a truncation radius for the planetary mass companion surface density of  $<135$  au at 95 per cent confidence.

**Key words:** instrumentation: adaptive optics – instrumentation: high angular resolution – methods: statistical – techniques: image processing – stars: early-type.

## 1 INTRODUCTION

Stellar properties are an important metric in the search for planets, as they guide the target selection for detection surveys. In particular, stellar mass and metallicity are significant quantities in determining both the formation and evolution of stars and planets (Johnson et al. 2010). Several radial velocity (RV) studies have shown that the giant planet frequency increases with stellar metallicity (Santos, Israelian & Mayor 2004; Fischer & Valenti 2005). The giant planet population as a function of stellar mass, however, is not consistent between different planet detection techniques (Quanz et al. 2012; Vigan et al. 2012; Clanton & Gaudi 2014). While progress has been made in linking the RV and microlensing populations (Clanton & Gaudi 2014), this is a challenging problem involving the synthesis of different biases and parameter spaces covered by all the detection techniques.

Gas giant planets ( $>1 M_{\text{Jup}}$ ) are the only directly imaged planets thus far, due to their increased self-luminous thermal emission and decreased contrast at infrared wavelengths with the star. Planet populations derived from RV surveys are often extrapolated to larger orbital separations to analyse the frequency of giant planets in direct imaging surveys (e.g. Lafrenière et al. 2007; Biller et al. 2013).

Planet formation scenarios (Alibert, Mordasini & Benz 2011) and simulations extrapolating RV planet populations (Johnson et al. 2007; Crepp & Johnson 2011) suggest that massive stars ( $>1.3 M_{\odot}$ ) are the most favourable targets for directly imaging planets, since they have proportionally more material to form giant planets. Indeed many directly imaged planetary mass companions have been found around A or F stars: HR8799 bcde (Marois et al. 2008; Marois, Macintosh & Véran 2010),  $\beta$  Pic b (Lagrange et al. 2009, 2010), HD 95086 b (Rameau et al. 2013b,c), HD 106906 b (Bailey et al. 2014). The detection of the HR8799 planets was the result of the Vigan et al. (2012) International Deep Planet Survey. Most surveys, however, have yielded null results (Kasper et al. 2007; Lafrenière et al. 2007; Chauvin et al. 2010, 2015; Heinze et al. 2010; Biller

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et al. 2013; Janson et al. 2013; Rameau et al. 2013a; Desidera et al. 2015). These null results are likely due to the lack of contrast at small orbital separations, where most planets are expected to be found. Typical detection limits for these surveys are 5–20  $M_{\text{Jup}}$  for >30 au. Planets are rare at large orbital separations (Lafrenière et al. 2007; Chauvin et al. 2010; Nielsen & Close 2010) but at Solar system scales ( $\leq 30$  au), stars are largely unexplored.

The main limitations for direct imaging are stellar ‘speckles’ which can appear brighter than a companion (Hinkley et al. 2009). Coronagraphs are used in order to reach smaller angular separations around stars. They reduce the diffraction due to scattered stellar light in the telescope optics but at a cost of reduced throughput. The Apodizing Phase Plate (APP; Kenworthy et al. 2010; Quanz et al. 2010, 2013) coronagraph suppresses the diffraction in a 180° wedge around a star, increasing the chances of detecting a very close-in companion. Several studies have demonstrated the APP’s capability of reaching  $\leq 30$  au (Quanz et al. 2011; Kenworthy et al. 2013; Meshkat et al. 2015).

We aim to probe down to Solar system scales ( $\leq 30$  au) around 13 A- and F-type main-sequence stars in order to detect giant planets as well as set constraints on the planet frequency. We use the APP coronagraph on NACO at the Very Large Telescope (VLT), the  $L'$ -band filter, and optimized principal component analysis (PCA) to achieve deep sensitivity limits (2–10  $M_{\text{Jup}}$  at  $\leq 30$  au).

In Section 2, we describe our target selection process, the coronagraphic observations, our data reduction method and how we determine the sensitivity of our data. In Section 3, we discuss the sensitivity achieved, our new detection of an  $M6.0 \pm 0.5$  dwarf companion to HD 984, and our re-detection of companions to HD 12894 and HD 20385. We run Monte Carlo simulations to determine the probability distribution of our results, in order to compare different planet population models for A-type stars. Our conclusions are in Section 4.

## 2 OBSERVATIONS AND DATA REDUCTION

Our sample was carefully selected to derive the best possible constraints on the frequency of giant exoplanets on Solar system scales: nearby, young, and massive main-sequence stars. Young planets are still warm from their contraction (Spiegel & Burrows 2012). By converting gravitational energy into luminosity, they are bright in the infrared. However, determining the age of a main-sequence star can be extremely challenging. One way to deal with this difficulty is to only select targets which are members of nearby associations with well-established ages. If they are all bona fide members of the group, we can assume the stars are of a similar age. Except for one,<sup>1</sup> our targets are all members of nearby young moving groups or associations:  $\beta$  Pic Moving Group ( $23 \pm 3$  Myr; Mamajek & Bell 2014), Tuc-Hor Association (40 Myr; Kraus et al. 2014), AB Dor Association ( $125 \pm 15$  Myr; Barenfeld et al. 2013). Nearby stars allow us to search for companions at smaller physical separations. We aim to reach planet sensitivity on Solar system scales, where we expect more planets to reside (Lafrenière et al. 2007; Chauvin et al. 2010; Nielsen & Close 2010). Thus, we have selected only stars which are less than 66 pc away.

<sup>1</sup> At the time of our observations, HD 984, was believed to be a 30 Myr member of Columba association. Based on our detection of a low-mass stellar companion to HD 984 and independent isochrone fitting, we estimate the age of HD 984 to be  $115 \pm 85$  Myr (Meshkat et al., 2015).

**Table 1.** Overview of stellar values used for each target.

Target	Mass ( $M_{\odot}$ )	$L'$ mag	Spectral type	Distance (pc)	Age (Myr)
HD 203	1.40	5.2	F3V	$39.4 \pm 0.6$	23
HD 12894	1.39	5.5	F4V	$47.8 \pm 1.0$	40
HD 25457	1.21	4.3	F6V	$18.8 \pm 0.1$	125
HD 35114	1.16	6.2	F6V	$8.3 \pm 0.9$	40
HD 20385	1.13	6.4	F6V	$49.2 \pm 1.5$	40
HD 102647	1.9	1.9	A3Va	$11.0 \pm 0.1$	40
HD 984	1.18	6.0	F7V	$47.1 \pm 1.4$	$115 \pm 85$
HD 13246	1.18	6.2	F7V	$44.2 \pm 0.9$	40
HD 40216	1.24	6.2	F7V	$54.4 \pm 1.3$	40
HD 30051	1.38	6.0	F2/3IV/V	$63.6 \pm 4.2$	40
HD 25953	1.16	6.6	F5	$55.2 \pm 2.9$	125
HD 96819	2.09	5.2	A1V	$55.6 \pm 1.7$	23
HD 123058	1.30	6.7	F4V	$64.1 \pm 3.5$	40

*Notes.* Distances are extracted from parallaxes in the *Hipparcos* catalogue (van Leeuwen 2007). The  $L'$ -band mag is converted from  $K$ -band mag in the 2MASS survey (Skrutskie et al. 2006) to using Cox (2000). The masses are from Casagrande et al. (2011) and Chen et al. (2014). All ages are based on membership in nearby young moving groups or associations, taken from Mamajek & Bell (2014), Kraus et al. (2014), Luhman, Stauffer & Mamajek (2005), Barenfeld et al. (2013), except for HD 984 which we compute in Meshkat et al. (2015). The bottom six targets were only observed in one APP hemisphere.

At the time of selection, most<sup>2</sup> of the targets were known to be single stars (Pourbaix et al. 2004; Mason et al. 2001) and not in the denser nucleus of their association. However, shortly after our survey was completed, a companion was discovered around one of our targets, HD 12894, by Biller et al. (2013) and Rameau et al. (2013a). Another target, HD 20385, was found to have a companion shortly after our data were acquired (Hartkopf, Tokovinin & Mason 2012).

### 2.1 Observations at the VLT

Data were obtained for 13 targets from 2011 to 2013 (088.C-0806(B), 089.C-0617(A) PI: Sascha Quanz) at the VLT/UT4 with NACO (Lenzen et al. 2003; Rousset et al. 2003) and the APP coronagraph (Kenworthy et al. 2010). The variation in the observing time for each target depends on the observing conditions on the night; if the observing conditions fell below a threshold during the night, the data acquisition was cancelled. Data were obtained with the L27 camera, in the  $L'$ -band filter ( $\lambda = 3.80 \mu\text{m}$  and  $\Delta\lambda = 0.62 \mu\text{m}$ ) and the NB 4.05 filter ( $\lambda = 4.051 \mu\text{m}$  and  $\Delta\lambda = 0.02 \mu\text{m}$ ) depending on the star’s  $L'$ -band magnitude. The visible wavefront sensor was used with each target star as its own natural guide star. We observed in pupil tracking mode to perform Angular Differential Imaging (ADI; Marois et al. 2006). We intentionally saturated the point spread function (PSF) core (on average out to  $\sim 0.08$  arcsec) to increase the signal-to-noise (S/N) from potential companions in each exposure. Unsaturated data were also obtained to calibrate photometry relative to the central star.

The APP generates a dark D-shaped wedge on one half of a target. Excess scattered light is increased on the other side of the target, which is not used in the data analysis. Two data sets were obtained with different initial position angles (P.A.) for full 360° coverage around the target star. Data were obtained in cube mode. Table 1 lists the stellar properties for each of our targets. Table 2

<sup>2</sup> HD 20385 was known to have a wide binary 12 arcsec away.

**Table 2.** Observing Log for NACO/VLT 088.C-0806(B) and 089.C-0617(A).

Target	Observation dates UT (Hem 1, Hem 2)	Number of data cubes	Total integration time (min)	On-sky rotation ( $^{\circ}$ )	Average DIMM seeing (arcsec)
HD 203	2011 Oct 12, 2011 Nov 07	154, 64	76.8, 58.0	46.65, 60.43	0.90, 1.19
HD 12894	2011 Dec 10, 2011 Dec 24	65, 55	55.6, 47.1	31.97, 27.92	0.78, 1.23
HD 25457	2011 Dec 11, 2011 Dec 21	71, 65	43.4, 39.8	28.63, 25.92	1.44, 0.65
HD 35114	2011 Dec 13, 2012 Jan 02	35, 35	30.3, 30.3	31.98, 28.20	0.75, 1.02
HD 20385	2011 Dec 21, 2012 Jan 08	47, 35	40.4, 30.3	30.54, 24.61	1.82, 1.25
HD 102647	2012 Jun 01, 2013 Apr 26	47, 56	47.3, 56.2	20.34, 24.71	1.61, 0.76
HD 984	2012 Jul 18, 2012 Jul 20	59, 65	54.5, 59.9	47.41, 42.46	0.65, 0.86
HD 13246	2011 Dec 07, –	107, –	90.9, –	45.43, –	0.99, –
HD 40216	2012 Jan 03, –	11, –	10.1, –	11.74, –	0.88, –
HD 30051	2012 Jan 07, –	56, –	48.0, –	2.7, –	1.68, –
HD 25953	2012 Jan 13, –	79, –	67.3, –	42.76, –	0.77, –
HD 96819	2012 May 02, –	49, –	47.3, –	105.46, –	0.64, –
HD 123058	2012 May 21, –	62, –	63.5, –	29.44, –	0.77, –

*Notes.* Data are in chronological order based on first Hemisphere observed. The last six targets were only observed in one APP hemisphere. Targets are listed in the same order as Table 1.

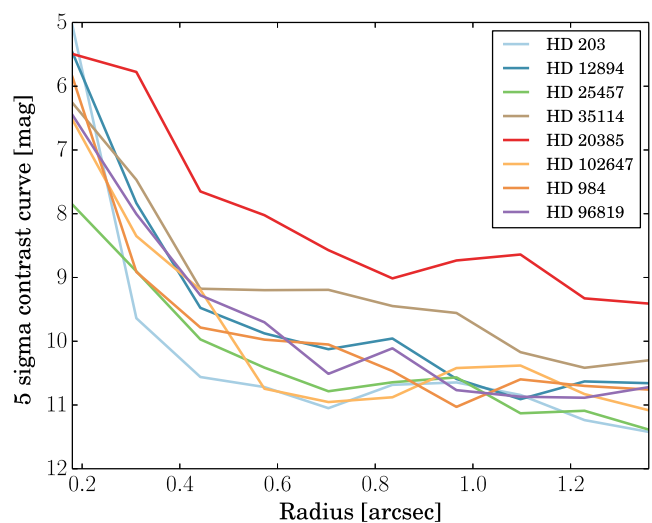
lists the observing conditions for all the data obtained. 13 targets were observed in at least one APP hemisphere.

## 2.2 Data reduction

A dither pattern on the detector was used to subtract sky background and detector systematics from the raw data, as detailed in Kenworthy et al. (2013). Subtracted data cubes are centroided and averaged over. The two APP hemispheres obtained for each target must be processed separately, since they were observed on different nights and thus have different speckle noise patterns. Optimized PCA was run on both of the APP hemispheres independently for each target, following Meshkat et al. (2014). This involves creating a linear combination of principal components (PCs) from the data itself in order to model and subtract away the stellar diffraction. Only the  $180^{\circ}$  D-shaped dark hemisphere was used in the PCA analysis. We fixed the number of PCs at approximately 10 per cent the number of input frames, as this yields the optimal PSF subtraction close ( $<1.0$  arcsec) to the star. We searched for point sources using this method for all 13 of our targets, despite not having full  $360^{\circ}$  coverage for 6 of them.

We injected fake planets into our data (before PCA processing) in order to determine the  $5\sigma$  sensitivity limit for each target. Unsaturated data of the star were used to inject the fake planets. We scaled the unsaturated data to the same exposure as the saturated data. The star was added to the data with a contrast of 5–12 mag in steps of 1 mag and from 0.18 to 1.36 arcsec in steps of 0.13. The outer radius limit was chosen because the field-of-view (FOV) of the APP is limited to only the upper quarter of the detector (Kenworthy et al. 2010). The planet injected data were processed with PCA, de-rotated, and averaged over for the final image with north facing up.

The final image was smoothed by a  $\lambda/D$  aperture, in order to remove features which are not the expected planet size or shape (Amara & Quanz 2012; Bailey et al. 2013). We define the S/N of the injected planet to be the value of a single pixel at the location of the planet divided by the root mean square (rms) of a ring around the star at the angular separation of the planet, excluding the planet itself. Only the statistically independent pixels (one smoothing kernel apart) were used to compute the rms. Fig. 1 shows the  $5\sigma$  contrast curves for all seven targets with two APP hemispheres and one target



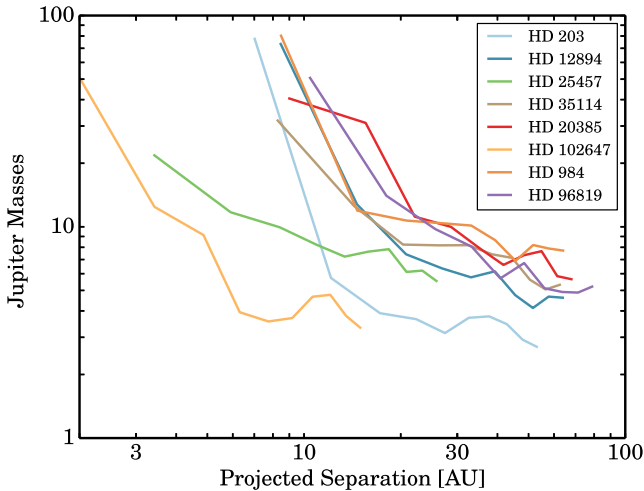
**Figure 1.**  $5\sigma$  contrast curves for the targets with full  $360^{\circ}$  APP coverage around the star and one target, HD 96819, with nearly  $360^{\circ}$  coverage.

(HD 96819) with nearly full sky coverage in one APP hemisphere.<sup>3</sup> For targets with two APP hemispheres, fake planets were added at a fixed P.A. in each hemisphere. The average S/N of the injected fake planets in each hemisphere is used (at the same separation). In the overlapping region between the two hemispheres, the number of frames varies slightly. However, since these regions are small and the number of frames never varies by more than 20 per cent, the impact on the contrast curves is small.

On average, we achieved a contrast of 9 mag at 0.4 arcsec and 10–11 mag at  $>0.6$  arcsec. The decreased sensitivity at  $<0.7$  arcsec around HD 20385 is an outlier compared to the other targets. One possible explanation is the extremely bright companion detected at  $\sim 0.8$  arcsec (discussed in Section 3.2), which affects the PCA component determination.

We used the COND evolutionary tracks (Baraffe et al. 2003) to convert the contrast curves to planet mass detection limits (Fig. 2).

<sup>3</sup> HD 96819 has on sky rotation of  $105^{\circ}.46$ . Since we are in ADI mode, the  $180^{\circ}$  APP ‘dark hole’ region rotates on the sky and only an  $\sim 74^{\circ}.9$  wedge is missing.



**Figure 2.** Detection limits in Jupiter masses versus projected separation in au for all targets with full APP coverage (and HD 96819). We are sensitive to planet mass companions ( $<12M_{\text{Jup}}$ ) for all of our targets, except HD 984. HD 102647 is more sensitive at smaller projected separation because it is much closer than the rest of the targets (11 pc). We do not plot the sensitivity beyond 1.5 arcsec for each target, due to the limited FOV of the APP.

For all but one of our targets,<sup>4</sup> we were sensitive to planetary mass objects ( $<12M_{\text{Jup}}$ ) at different projected separations, depending on the target distance. The outer radius for the sensitivity curves were based on the limited FOV of the APP (Kenworthy et al. 2010). Thus, while the sensitivity curves appear to flatten out, we cannot extend these curves beyond 1.5 arcsec since we were not sensitive completely around the star.

### 3 RESULTS

We detect one new  $M6.0 \pm 0.5$  dwarf companion to HD 984, and re-detect companions to HD 12894 and HD 20385. To estimate the astrometry, we first determined the centroid of the three companions. In this way, we verified that our star was well centred in our data. Since the APP has an asymmetric PSF, this step is crucial. We then injected fake negative companions at the location of the companion to determine the photometry and astrometry with error bars. We also varied the flux of the fake negative companions to cancel out the companion flux, which in some cases varies up to 20 per cent due to atmospheric fluctuations.

We iteratively converged on the P.A., angular separation, and  $\Delta$  magnitude by varying the position and contrast and taking a  $\chi^2$  minimization over the  $\lambda/D$  aperture at the location of the companion. For the very bright companions to HD 12894 and HD 20385, we determined the photometry and astrometry from ADI alone rather than PCA. Minor variations in the brightness and position of the companion in each frame can lead to ‘striping’ in the final PCA processed image. This striping occurs when PCA fits the remaining flux around of the companion after the fake companion is subtracted, since we never perfectly subtract the companion in individual frames due to seeing variability. Table 3 lists the properties of the companions we detect based on our APP data. The error on the P.A. includes uncertainties from true north orientation, based on direct imaging observations ( $\sim 0.5$ ; Rameau et al. 2013a).

<sup>4</sup> We were not sensitive to planet masses around HD 984, since it is much older than previously reported (Meshkat et al., 2015).

#### 3.1 HD 12894

Rameau et al. (2013a) and Biller et al. (2013) reported the discovery of HD 12894 B. Rameau et al. (2013a) detected a  $\Delta L' = 2.7 \pm 0.1$  mag point source 14 au from the star. They concluded that it was likely bound to the star, based on a non-detection in 1999 2MASS data, because a background source would be detected due to proper motion of HD 12894. Based on the contrast and an age of 30 Myr, they concluded that the companion was a  $0.8M_{\odot}$  K6 star. Biller et al. (2013) concluded it was a comoving  $0.46 \pm 0.08M_{\odot}$  companion 15.7  $\pm$  1.0 au away from its star, based on contrast of  $\Delta H = 3.0$  mag. The discovery was made with the VLT/NACO instrument in the  $L'$  band as well as the NICI instrument on Gemini South in the  $H$  band, respectively.

At the time our data were acquired, the companion was not known. We detect the companion with a  $\Delta L' = 2.89 \pm 0.14$  mag at a PA of  $240^{\circ}24 \pm 1^{\circ}27$  and separation of  $0.31 \pm 0.01$  arcsec. This corresponds to a projected separation of  $14.8 \pm 0.8$  au, with  $d = 47.8 \pm 1.0$  pc for the distance to the star (van Leeuwen 2007). Fig. 3 shows the ADI processed image of the companion. Using the COND evolutionary models (Baraffe et al. 2003) and the age of the star (40 Myr; Kraus et al. 2014), we estimate the mass of the companion is  $0.53 \pm 0.04M_{\odot}$ . Our analysis of this companion is consistent with Biller et al. (2013).

#### 3.2 HD 20385

At the time we proposed to observe this target, it was a known wide binary, with a companion TOK 78 B 12 arcsec away. Hartkopf et al. (2012) reported the discovery of a new, close companion around HD 20385 at 0.88 arcsec,  $\Delta I = 3.5$  mag,  $\Delta y = 5.2$  mag. They estimated the companion has a period of 200 years. Due to its variable radial velocity, they suggested the companion could be two unresolved companions.

We detect the companion in our data at  $0.87 \pm 0.01$  arcsec with a P.A. of  $118^{\circ}67 \pm 0^{\circ}49$  and contrast of  $\Delta L' = 2.52 \pm 0.10$  mag. Using the stellar distance of  $49.2 \pm 1.5$  pc (van Leeuwen 2007), this companion is at a projected separation of  $42.8 \pm 1.8$  au. Fig. 3 shows the ADI processed image of the companion to HD 20385. The companion’s PSF clearly shows the APP PSF structure, with the bright lobes smeared due to the rotation on the sky. The age of the system is 40 Myr based on membership in the Tuc-Hor Association (Kraus et al. 2014). Using COND models (Baraffe et al. 2003), we estimate the companion to have a mass of  $0.33 \pm 0.03M_{\odot}$ .

#### 3.3 HD 984

As reported in Meshkat et al. (2015), we detected a companion around HD 984 in our APP data, as well as archival direct imaging data. Fig. 3 shows our PCA reduced image with 20 PCs. We confirmed the companion is comoving with HD 984 and determined that is an  $M6.0 \pm 0.5$  dwarf based on Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) integral field spectroscopy (see Table 3).

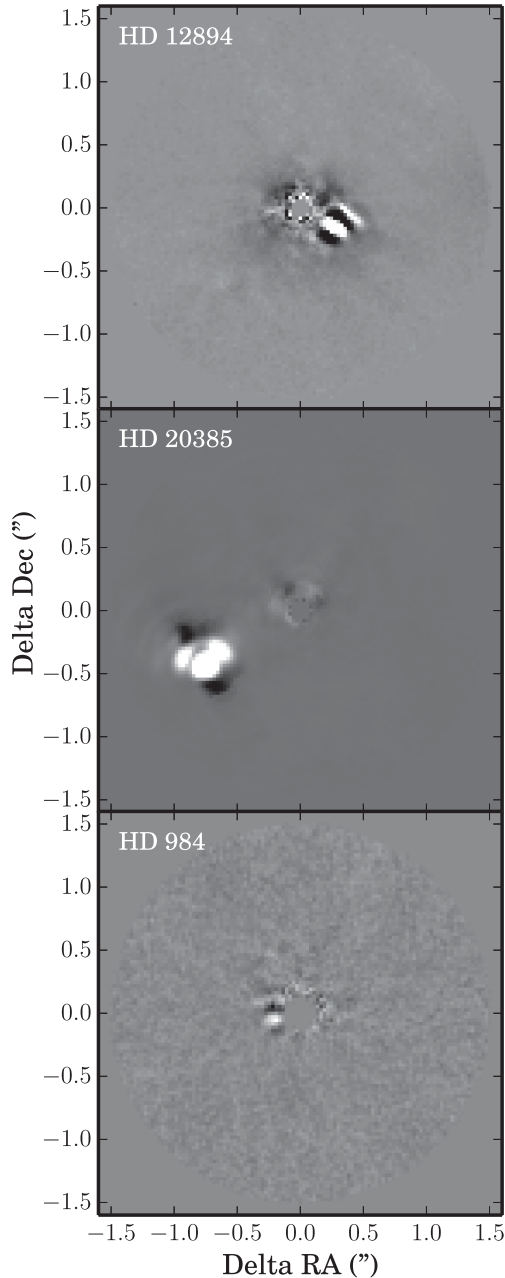
#### 3.4 Monte Carlo simulations

We ran 10 000 Monte Carlo simulations of the target stars in order to determine the probability distribution of detecting substellar companions in our data assuming power-law slopes for the mass and semimajor axis distributions, for both planets and brown dwarfs (BDs), following Reggiani et al. (2015). For the BD distribution,



**Table 3.** Companion properties of our targets.

Target	Date	Separation (arcsec)	P.A. (deg)	$\Delta L'$ (mag)	Mass ( $M_{\odot}$ )
HD 12894 B	2011 Nov 24	$0.31 \pm 0.01$	$240.24 \pm 1.27$	$2.89 \pm 0.14$	$0.53 \pm 0.04$
HD 20385 B	2011 Dec 21	$0.87 \pm 0.01$	$118.67 \pm 0.49$	$2.52 \pm 0.10$	$0.33 \pm 0.03$
HD 984 B	2012 July 18	$0.19 \pm 0.02$	$108.9 \pm 3.1$	$6.0 \pm 0.2$	$0.11 \pm 0.01$



**Figure 3.** Top: HD 12894 ADI processed image, with the companion at 0.31 arcsec. Middle: HD 20385 ADI processed image, with the companion at 0.87 arcsec. The shape of the companion PSF is due to the APP PSF. Bottom: HD 984 PCA processed image with the companion 0.19 arcsec from star.

we adopted the stellar companion mass ratio distribution (CMRD) from Reggiani & Meyer (2013) and a lognormal separation distribution (De Rosa et al. 2014). We included all of our targets in these simulations, including those with only one APP hemisphere cov-

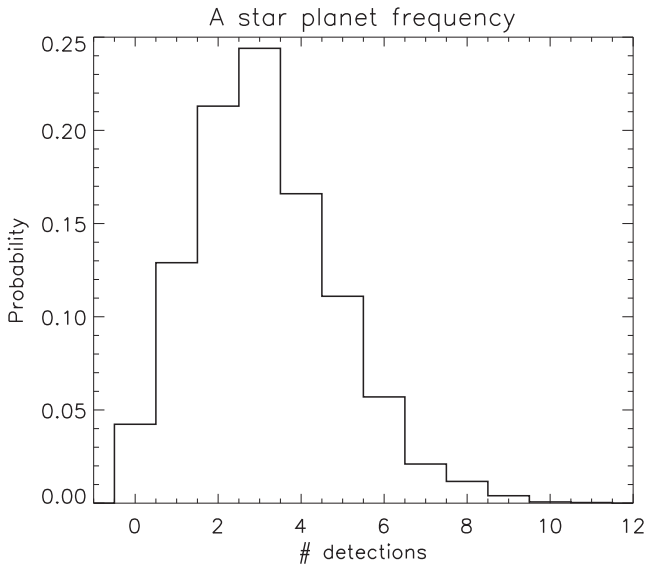
erage. In order to account for the targets without full sky coverage in our simulations, we multiplied the overall planet frequency per target by the fraction of sky coverage achieved.

For the planets, we adopted a model distribution for A-type primaries which assumes the mass and separation distributions measured by RV surveys for solar-type stars, and extrapolated at larger separations (Heinze et al. 2010, based on Cumming et al. 2008). According to Cumming et al. (2008), the planet mass and semimajor axis distributions are modelled with power laws of index  $\alpha = -1.31$  and  $\beta = -0.61$  ( $dN \sim M^{-1.31} dM$  and  $dN \sim a^{-0.61} da$ ). To account for the A-type primary planet frequency, we adopted the values corresponding to the median sensitivity achieved in the RV data presented in Bowler et al. (2010) and Johnson et al. (2010) ( $f = 11 \pm 2$  per cent for planets in the ranges  $0.5\text{--}14 M_{\text{Jup}}$  and  $0.1\text{--}3.0$  au).

For both planets and BDs, we assume a random distribution of inclinations and the eccentricity distribution given by Jurić & Tremaine (2008). In each simulation, we assigned each target a number of planets and BDs from a Poisson distribution, according to the average number of planets and BDs per star, calculated from the aforementioned distribution. We also varied the outer radius cutoff: 20, 30, 80, 100, 120, 130 and 140 au. The introduction of an upper limit for the planet separation distribution has been suggested by the results of previous direct imaging surveys (Chauvin et al. 2010; Vigan et al. 2012).

If a target turns out to have one or more companions in the simulation, we assigned each companion a mass and the orbital parameters (semimajor axis, eccentricity, inclination) randomly drawn from the assumed distributions. The mass is converted into apparent magnitude, given the distance and age of the star and assuming the same family of evolutionary models as in Section 2.2 (COND; Baraffe et al. 2003). The semimajor axis was converted into a projected separation, given the eccentricity and inclination and taking into account the time spent on the orbit. If the combination of brightness and separation lies above the contrast curve (Fig. 1), then the companion is detectable. Thus, at the end of every simulation, we know how many companions are created and how many are detected. After 10 000 simulations, we determined the average detection probability for our A and F main-sequence star survey (Fig. 4). Three companions were detected in this survey, but none of them were substellar ( $<80 M_{\text{Jup}}$ ). Thus, the probability of detecting 0 companions for each model is given in Table 4.

Given these probabilities, our null result allows us to reject the A-type star model with a scaled up planet frequency for  $r_{\text{cutoff}} > 135$  au, at 95 per cent confidence. This null result is also consistent with previous surveys that found that high-mass planets at large orbital separations are rare (Biller et al. 2013; Nielsen et al. 2013; Chauvin et al. 2015; Desidera et al. 2015). We note that unlike larger surveys, our simulations include both the planetary-mass companions as well as an extrapolation of the BD companion mass ratio distribution. Since we expect a contribution from both populations in the total number of detections, a null result is more constraining than a planet population alone. We also adopt a higher planet frequency (as expected for A type stars) compared to the standard planet



**Figure 4.** Detection probability distributions for our survey, assuming an outer-radius cutoff of 140 au for the planet separation distributions (Reggiani et al., 2015). With our null result, we rule out the A-star frequency beyond a cutoff of 135 au at the 95 per cent confidence level.

**Table 4.** Probability of a null result in our A and F main-sequence star survey.

$r_{\text{cutoff}}$ (au)	$P(0)$ (per cent)	A-type star planet frequency
20		80
30		70
80		25
100		14
120		8
130		6
140		4

frequency measured by Cumming et al. (2008) for solar-type stars. If the expected number of detections is higher, a null detection result allows one to place more stringent constraints. This is why our survey of 13 targets places comparable constraints compared to larger surveys.

Based on RV measurements of A stars, Bowler et al. (2010) suggest positive values for the power-law indexes of the mass and separation distributions, with high confidence. According to our Monte Carlo simulations, if we assume positive power-law indexes, the probability of a null result is less than 0.1 per cent, regardless of the planet frequency or the radius cutoff assumed. As suggested by Vigan et al. (2012), the inconsistency of direct imaging survey results with the distribution parameters from RV observations around A-stars (Bowler et al. 2010) suggests that different planet populations are probed by RV measurements at small separations than direct imaging at wide separations.

#### 4 CONCLUSIONS

We present the results from a survey of carefully selected A- and F-type main-sequence stars, searching for exoplanet companions. We aim to put direct imaging constraints on the occurrence of substellar companions as a function of stellar mass. We obtained data on 13 nearby ( $d < 65$  pc), young ( $< 125$  Myr) targets with the APP coronagraph on NACO/VLT. We are sensitive to planet masses ( $2\text{--}10 M_{\text{Jup}}$ ) on Solar system scales ( $\leq 30$  au) for all but one

of our targets. We detected a new  $M6.0 \pm 0.5$  dwarf companion to HD 984 and confirm stellar companions to HD 12894 and HD 20385, discovered shortly after our survey data were acquired. Our photometry and astrometry for these companions are consistent with the values reported at the time of their discovery (Hartkopf et al. 2012; Biller et al. 2013). We found zero false positives in our  $L'$ -band data, as all of our detected point sources were bona fide companions. We perform Monte Carlo simulations to determine the expected probability of detecting low-mass companions in our survey, based on our sensitivity and assumed semimajor axis distributions. Our non-detection of substellar companions ( $< 80 M_{\text{Jup}}$ ) allows us to rule out the A-star frequency model distribution for  $> 135$  au, with 95 per cent confidence.

#### ACKNOWLEDGEMENTS

TM and MAK acknowledge funding under the Marie Curie International Reintegration Grant 277116 submitted under the Call FP7-PEOPLE-2010-RG. Part of this work has been carried out within the frame of the National Centre for Competence in Research PlanetS supported by the Swiss National Science Foundation. SPQ and MRM acknowledge the financial support of the SNSF. EEM acknowledges support from NSF award AST-1313029. This work is based on the observations collected at the European Organization for Astronomical Research in the Southern hemisphere, Chile, ESO under programme numbers 089.C-0617(A) and 089.C-0149(A). This paper makes use of the SIMBAD Database and the VizieR Online Data Catalog.

#### REFERENCES

- Alibert Y., Mordasini C., Benz W., 2011, *A&A*, 526, A63  
 Amara A., Quanz S. P., 2012, *MNRAS*, 427, 948  
 Bailey V. et al., 2013, *ApJ*, 767, 31  
 Bailey V. et al., 2014, *ApJ*, 780, L4  
 Baraffe I., Chabrier G., Barman T. S., Allard F., Hauschildt P. H., 2003, *A&A*, 402, 701  
 Barenfeld S. A., Bubar E. J., Mamajek E. E., Young P. A., 2013, *ApJ*, 766, 6  
 Biller B. A. et al., 2013, *ApJ*, 777, 160  
 Bowler B. P. et al., 2010, *ApJ*, 709, 396  
 Casagrande L., Schönrich R., Asplund M., Cassisi S., Ramírez I., Meléndez J., Bensby T., Feltzing S., 2011, *A&A*, 530, A138  
 Chauvin G. et al., 2010, *A&A*, 509, A52  
 Chauvin G. et al., 2015, *A&A*, 573, A127  
 Chen C. H., Mittal T., Kuchner M., Forrest W. J., Lisse C. M., Manoj P., Sargent B. A., Watson D. M., 2014, *ApJS*, 211, 25  
 Clanton C., Gaudi B. S., 2014, *ApJ*, 791, 90  
 Cox A. N., 2000, in Arthur N. C., ed., *Allen's Astrophysical Quantities*, 4th ed., Am. Inst. Phys., AIP Press, Springer-Verlag, New York  
 Crepp J. R., Johnson J. A., 2011, *ApJ*, 733, 126  
 Cumming A., Butler R. P., Marcy G. W., Vogt S. S., Wright J. T., Fischer D. A., 2008, *PASP*, 120, 531  
 De Rosa R. J. et al., 2014, *MNRAS*, 437, 1216  
 Desidera S. et al., 2015, *A&A*, 573, A126  
 Fischer D. A., Valenti J., 2005, *ApJ*, 622, 1102  
 Hartkopf W. L., Tokovinin A., Mason B. D., 2012, *AJ*, 143, 42  
 Heinze A. N., Hinz P. M., Sivanandam S., Kenworthy M., Meyer M., Miller D., 2010, *ApJ*, 714, 1551  
 Hinkley S. et al., 2009, *ApJ*, 701, 804  
 Janson M. et al., 2013, *ApJ*, 773, 73  
 Johnson J. A., Butler R. P., Marcy G. W., Fischer D. A., Vogt S. S., Wright J. T., Peek K. M. G., 2007, *ApJ*, 670, 833  
 Johnson J. A., Aller K. M., Howard A. W., Crepp J. R., 2010, *PASP*, 122, 905

- Jurić M., Tremaine S., 2008, *ApJ*, 686, 603
- Kasper M., Apai D., Janson M., Brandner W., 2007, *A&A*, 472, 321
- Kenworthy M., Quanz S., Meyer M., Kasper M., Girard J., Lenzen R., Codona J., Hinz P., 2010, *The Messenger*, 141, 2
- Kenworthy M. A., Meshkat T., Quanz S. P., Girard J. H., Meyer M. R., Kasper M., 2013, *ApJ*, 764, 7
- Kraus A. L., Shkolnik E. L., Allers K. N., Liu M. C., 2014, *AJ*, 147, 146
- Lafrenière D. et al., 2007, *ApJ*, 670, 1367
- Lagrange A.-M. et al., 2009, *A&A*, 493, L21
- Lagrange A.-M. et al., 2010, *Science*, 329, 57
- Lenzen R. et al., 2003, in Iye M., Moorwood A. F. M., eds, *Proc. SPIE Conf. Ser.*, Vol. 4841, *Instrument Design and Performance for Optical/Infrared Ground-based Telescopes*, SPIE, Bellingham, p. 944
- Luhman K. L., Stauffer J. R., Mamajek E. E., 2005, *ApJ*, 628, L69
- Mamajek E. E., Bell C. P. M., 2014, *MNRAS*, 445, 2169
- Marois C., Lafrenière D., Doyon R., Macintosh B., Nadeau D., 2006, *ApJ*, 641, 556
- Marois C., Macintosh B., Barman T., Zuckerman B., Song I., Patience J., Lafrenière D., Doyon R., 2008, *Science*, 322, 1348
- Marois C., Macintosh B., Véran J.-P., 2010, in Ellerbroek B. L., Hart M., Hubin N., Wizinowich P. L., eds, *Proc. SPIE Conf. Ser.*, Vol. 7736, *Adaptive Optics Systems II*, SPIE, Bellingham, p. 77361J
- Mason B. D., Wycoff G. L., Hartkopf W. I., Douglass G. G., Worley C. E., 2001, *AJ*, 122, 3466
- Meshkat T., Kenworthy M. A., Quanz S. P., Amara A., 2014, *ApJ*, 780, 17
- Meshkat T. et al., 2015, *MNRAS*, in press
- Meshkat T., Bailey V. P., Su K. Y. L., Kenworthy M. A., Mamajek E. E., Hinz P. M., Smith P. S., 2015, *ApJ*, 800, 5
- Nielsen E. L., Close L. M., 2010, *ApJ*, 717, 878
- Nielsen E. L. et al., 2013, *ApJ*, 776, 4
- Pourbaix D. et al., 2004, *A&A*, 424, 727
- Quanz S. P. et al., 2010, *ApJ*, 722, L49
- Quanz S. P., Schmid H. M., Geissler K., Meyer M. R., Henning T., Brandner W., Wolf S., 2011, *ApJ*, 738, 23
- Quanz S. P., Lafrenière D., Meyer M. R., Reggiani M. M., Buenzli E., 2012, *A&A*, 541, A133
- Quanz S. P., Amara A., Meyer M. R., Kenworthy M. A., Kasper M., Girard J. H., 2013, *ApJ*, 766, L1
- Rameau J. et al., 2013a, *A&A*, 553, A60
- Rameau J. et al., 2013b, *ApJ*, 772, L15
- Rameau J. et al., 2013c, *ApJ*, 779, L26
- Reggiani M., Meyer M. R., 2013, *A&A*, 553, A124
- Reggiani M. et al., 2015, *MNRAS*, in press
- Rousset G. et al., 2003, in Wizinowich P. L., Bonaccini D., eds, *Proc. SPIE Conf. Ser.*, Vol. 4839, *Adaptive Optical System Technologies II*, SPIE, Bellingham, p. 140
- Santos N. C., Israelian G., Mayor M., 2004, *A&A*, 415, 1153
- Skrutskie M. F. et al., 2006, *AJ*, 131, 1163
- Spiegel D. S., Burrows A., 2012, *ApJ*, 745, 174
- van Leeuwen F., 2007, *A&A*, 474, 653
- Vigan A. et al., 2012, *A&A*, 544, A9

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