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# Searching for massive extrasolar planets around young and nearby stars: from NACO to CHEOPS

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**Abstract.** We report on a survey devoted to the search of exo-planets around young and nearby stars carried out with NACO at the VLT. The detection limit for 28 among the best available targets vs. the angular separation from the star is presented. The non-detection of any planetary mass companion in our survey is used to derive, for the first time, the frequency of the upper limit of the projected separation planet/stars. In particular, we find that in 50% of cases, no 5$M_J$ planet (or more massive) has been detected at projected separations larger than 14 AU and no 10$M_J$ planet (or more massive) has been detected at projected separations larger than 8.5 AU. The excellent sensitivity reached by our study leads to a much lower upper limit of the projected separation planet-star compared with previous studies. For our closest target (V2306 Oph - d = 4.3 pc) it is shown that it would be possible to detect a 10$M_J$ planet at a minimum projected separation from the star of 1 AU and a 5$M_J$ planet at a minimum projected separation of 3.7 AU. Our results are discussed with respect to forthcoming observational strategies (Simultaneous Differential Imaging technique) and future planet finder observations from the ground.

**Key words.** binaries: close— planetary system— stars:low-mass, brown dwarfs

## 1. Introduction

It can be shown that young planets can be detected with adaptive optics (AO) imaging techniques at 8-10 meter telescopes if they are sufficiently distant from their parent star. Since it is reasonable to assume a coevality between the parent star and the planet, we can retrieve from atmospherical models (Burrows et al. 1997, Baraffe et al. 2003) that planets having a mass in the range 3-10 $M_J$ and orbiting around young late-type stars (10-200 Myr) have a typical brightness contrast with respect to the parent star of the order of $10^2$-$10^6$, corresponding to a magnitude difference of $\Delta M$ of 5-15 mag. This means that a planet can be detected at a few tens of AUs from parent stars having distances $\sim$ 50 pc.

According to recent statistical results (e.g. Marcy et al. 2003), most of known exo-planets orbit at distances smaller than 1 AU and the semi-major axes of the exo-planets found thus far are not larger than ~6 AU. Since these results are heavily biased towards short separa-

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tions the derived major-axis distribution is certainly not representative. Not much is known at present about potential planets that could exist at distances larger than about 6 AU. Besides, there are models (for example the gravitational scattering model) that claim that in multi-planetary systems, due to gravitational interactions between the planets, it can happen that the lightest objects are ejected on hyperbolic trajectories and some planets can move on stable orbits having a distance of a few tens AU from the parent star. Such models were proposed by Weidenschilling & Marzari (1996) and Rasio & Ford (1996) and studied more recently by Papaloizou & Terquem (2001).

There are thus elements that indicate that such planets might exist at large distances from the central star. For this reason we planned and performed an extended survey aiming to search for massive exo-planets orbiting around nearby and young stars using one of the best available instruments at the present time for high-contrast AO imaging observations: NACO at the Very Large Telescope (VLT). We report here the principal results obtained and we discuss the forthcoming observational strategies that will permit us to reach better contrast at small angular separation and to improve the reliability of the statistic that we obtained.

## 2. Results

We refer to Masciadri et al. (2004) for detailed informations on the target selection, observational strategy employed in the survey and data processing. Here we briefly summarize the principal informations. Around 30 targets (nearby stars) were observed during 3 runs. The targets are placed at d $\leq$ 77 pc (with 70 % of them in the first 32 pc), they have an age of 1-200 Myr and late spectral type (K and M). Firstly we observed each target in a narrow band filter for a few minutes in order to obtain a non-saturated point spread function (PSF). Secondly, we obtained deep ($\sim$ 20 minutes) $K_s$ and H broadband observations of each target. Data were reduced using standard procedures to eliminate bad pixels, flat and background sky (IRAF and ECLIPSE). A dedicated pipeline has been employed to filter the low spatial frequencies in order to improve the detection limit at subarcsec distances (Masciadri et al. (2004)). Two different methods were used for the low spatial frequencies filtering.

We averaged the contrast $\Delta M$ obtained at $0\farcs5$ and $1''$ for all the observed targets having a total integration time within the range 20-30 minutes. We find, in the $K_s$ band, a $\Delta M$ = 9 mag at $0\farcs5$ and a $\Delta M$ = 11.5 mag at $1''$. We find, in $H$ band, a $\Delta M$ = 9.2 mag at $0\farcs5$ and a $\Delta M$ = 11.7 mag at $1''$. We recall that $0\farcs5$ corresponds, for our sample, to projected separations of 2-35 AU, $1''$ to projected separations of 4-70 AU. This illustrates nicely that NACO is a well performing instrument for high-contrast imaging observations.

No very promising massive-planet candidate was identified in our survey. Besides this we calculated the detection limit for 28 of these targets (Masciadri et al. 2004) and we retrieve the upper limit of the star/planet projected separation calculated for a potential 10 and 5 $M_J$ planet (Table 1). By analysing these results from a statistical point of view, we can calculate (Fig.1-Left) the cumulative distribution of the upper limit of the distance star/exo-planet for our sample of targets. The thin line represents the cumulative distribution obtained for $5M_J$ planets. We find that (Fig.1-Left), with respect to our sample of targets, in 50% of cases (median value), there are not planets at distances larger than 14 AU and, in 100% of cases, there are no planets at distances larger than 65 AU. We underline that we are considering a $5M_J$ planet just as a reference, but the same calculation could be done for more and/or less massive planets in the range 3-10 $M_J$. In the case of more massive planets, the cumulative distribution should have a medium value (50%) associated to an angular separation smaller than 14 AU. In the case of less massive planets, the cumulative distribution should have a medium value (50 %) associated to a angular separation larger than 14 AU. To better appreciate the sensitivity with respect to the mass of the planets we also calculated the cumulative distribution for $10M_J$ planets

(Fig.1-Left - bold line). We find that, in 50% of the cases (median value) there are no planets at distances larger than 8.5 AU and in 100% of the cases there are not planets at distances larger than 36 AU. The number given in Table 1 and the cumulative distribution illustrate that it is relatively unlikely that a massive planet exist beyond a certain distance from the star. For example the fact that no 5$M_J$ planet was found for 18 of our targets beyond 20 AU (see Table1) means that the likelood for the existence of such planets beyond this distance is ~ (1/18) % i.e. ~ 5.6%. This last estimation is useful for the reader to have an idea of how much the size of the sample affects the statistical results. We remind that we are using the term *probability* in a less conventional way. A precise (statistically speaking) definition of *probability* should need some positive detection that we obviously do not have.

## 3. Forthcoming observational strategies

The interesting question is now: *how can we improve our results to better constrain planet-formation models ?* It is evident that an increase of the achievable contrast at smaller angular separations shifts the medium value of the cumulative distributions to smaller angular separations (Fig.1-Left). This means that the upper limit of the projected separation star/exo-planet decreases. However, we note that, using the observational strategy employed in our survey, we can hardly improve the sensitivity at subarcsecond distances using a 8 meter class telescope as illustrated in Fig.1-Right. This figure shows the detection limit obtained for one of our targets for an integration time of 5, 10 and 22 minutes. The deep image was filtered from low spatial frequencies before we calculated the detection limit. We observe that, beyond 1″, the reachable contrast increases with increasing the integration time (~ 1 mag in 15 min). At distances smaller than 1″, on the contrary, a longer integration time does not increase the contrast because we are strongly limited by the speckle noise.

### 3.1. Simultaneous Differential Technique

The differential imaging technique proposed by Racine et al. (1999) is a rather efficient method to reduce the speckle noise at small angular separations from the central star. Images taken simultaneously at slightly different wavelengths are subtracted from each other. Since the speckle noise of both images is nearly the same[1], the speckle noise is eliminated in the resulting image providing one can sufficiently limit static aberrations. The differential technique finds a useful application in detecting cool methane-rich faint objects. Rosenthal et al. (1996) first proposed observations of the same star done simultaneously in two different wavelengths which are located *"on"* and *"off"* the methane ($CH_4$) absorption band. If one subtracts the image taken in the absorption band from the one taken outside the absorption band, planet/brown dwarf features appear in the continuum. The absorption at 1.62 $\mu$m, in the $CH_4$ band, is a clear signature of any object having temperature T ≤ 1300 K (giant exo-planets and T-type brown dwarfs).

We can thus increase the sensitivity (contrast) at subarcsecond distances using the recently implemented NACO/SDI (Simultaneous Differential Imager) instrument. This instrument permits to employ the differential technique in *H* band. Preliminary results (Close et al. 2004, Lenzen et al. 2004) indicate a $\Delta M$ ~ 11 mag at 0.″5 from the central star. Considering our averaged estimate of $\Delta M$ = 9.2 mag in the *H* band (see Section 2), we should gain ~ 2 mag in contrast using NACO/SDI at 0.″5 (see Fig.1-Right).

### 3.2. CHEOPS: a planet finder for the VLT

A further and fundamental improvement in contrast should be attained by future ground-based "planet finders", i.e. instruments supported by AO systems providing a better Strehl Ratio (the so called extreme Adaptive Optique). The contrast reachable by such an in-

[1] We precise that speckles of images taken at slightly different wavelengths match if frames are rescaled opportunely by a $\lambda_2/\lambda_1$ factor.

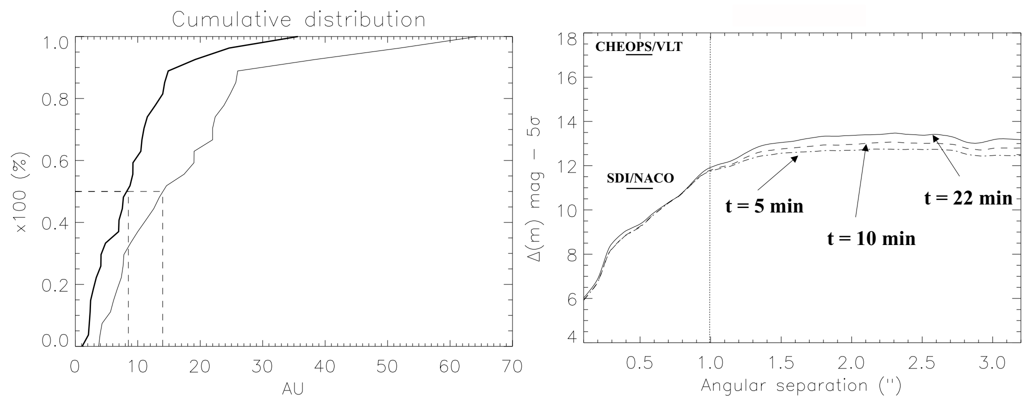


**Fig. 1. Left:** Cumulative distribution of the upper limit for the projected separation star/planet calculated with our sample of targets. Thin line: $5M_J$, bold line: $10M_J$. This distribution implies that in 50% of cases (median value) we have not found any $5M_J$ planets at distances larger than 14 AU and no $10M_J$ planets at distances larger than 8.5 AU. **Right:** Detection limit vs. angular separation of one target of the survey obtained with integration times of 5, 10 and 22 min. The two horizontal bars placed at 0.″5 mark the expected contrast reachable with SDI/NACO and CHEOPS (VLT planet finder - see text).

strument at 0.″5 should be $\Delta M \sim 17.5$ mag in *J*-*H* bands (see Fig.1-Right). We refer in particular to the top level requirements of CHEOPS, a second generation instrument for the VLT conceived for planet detection (Gratton et al. 2004). This instrument is planned to have two science arms. An integral field spectrograph (IFS), running in J and H band and optimized for the detection of *young targets* (i.e. those planets for which the intrinsic luminosity is dominant with respect to the light coming from the parent star and reflected by the planet) and an imager polarimeter ZIMPOL, running in I band and optimized for the detection of *old planets* (i.e. those planets for which the light coming from the parent star and reflected and polarized by the planet, is dominant with respect to the intrinsic luminosity of the planet). Both instruments will employ the differential technique i.e. they will both be able not only to detect planets but also to characterize their atmosphere. To give a quantitative estimate of the scientific impact that an instrument as CHEOPS should have in the searches of planets (we refer in this context to the same category of planets defined in this paper i.e. young and massive planets), we calculated, on the base of atmospherical models predictions, that in the case of a target placed at 10 *pc*, having an age of 10 Myr (i.e. a favourable case), CHEOPS will be able to detect as small as $0.3M_J$ planet at 5 AU. Assuming a farther target (d ~ 20 pc) having an age of ~ 200 Myr, CHEOPS will be able to detect as small as $1M_J$ planet at 10 AU. In other worlds, under a large set of parameter range comparable to those analysed in our survey, we can state that CHEOPS will be able to reach the detectivity limit of $1M_J$ planet at comparable angular separations and for a comparable sample of targets to those studied in this paper.

Of course the most challenging scientific goal of this planet finder will be the detection of a few $1M_J$ planet orbiting around solar-like star (~ 1Gyr) at $d \leq 5$ pc. In some cases it will be able to detect such planets with both instruments.

## 4. Conclusions

In this contribution we have presented results of a survey carried out with NACO at the VLT aiming to detect massive exo-planets (3-10 $M_J$) orbiting around 30 young (10-200 Myr)

**Table 1.** Targets, ages, distances of targets from the observer and upper limit of the star/planet projected separation in the cases of a $5M_J$ and a $10M_J$ planet.

| Targets | Age (Myr) | D (pc) | proj. sep.-AU ($5M_J$) | proj. sep.-AU ($10M_J$) |
|---|---|---|---|---|
| Hip 2729 | 35 | 49.5 | 64 | 36 |
| GJ 179 | 200 | 12.1 | 9 | 5 |
| GJ 182 | 35 | 26.7 | 19 | 11 |
| Hip 23309 | 12 | 26.3 | 11 | 7 |
| AO Men | 12 | 38.5 | 13 | 9 |
| BD +2° 1729 | 100 | 9.8 | 8 | 4 |
| LQ Hya | 50 | 18.3 | 22 | 8 |
| TWA 6A | 10 | 77.0 | 52 | 25 |
| BD 1° 2447 | 100 | 7.2 | 6 | 3 |
| TWA 5B | 10 | 50.0 | 10 | 7 |
| TWA 8A | 10 | 21.0 | 7 | 3 |
| TWA 8B | 10 | 21.0 | 7 | 2 |
| TWA 9A | 10 | 64.0 | 38 | 19 |
| TWA 9B | 10 | 64.0 | 22 | 13 |
| SAO 252852 | 100 | 16.4 | 19 | 10 |
| V343 Nor | 12 | 39.8 | 24 | 12 |
| V2306 Oph | 100 | 4.4 | 4 | 1 |
| HD 155555 AB | 12 | 31.4 | 22 | 11 |
| HD 155555 C | 12 | 31.4 | 13 | 8 |
| CD -64° 1208 | 12 | 29.2 | 15 | 9 |
| PZ Tel | 12 | 49.6 | 26 | 15 |
| GJ 799 A | 12 | 10.2 | 4 | 2 |
| GJ 799 B | 12 | 10.2 | 6 | 2 |
| GJ 803 (Au Mic) | 12 | 9.9 | 4 | 2 |
| BD -17° 6128 | 12 | 47.7 | 25 | 14 |
| GJ 813 | 200 | 13.6 | 8 | 4 |
| GJ 890 | 100 | 21.8 | 26 | 14 |
| HD 221503 | ≥ 100-200 | 13.9 | 17 | 9 |

and nearby ($d \leq 77$ pc with 70 % of them in the first 32 pc) stars.

No promising candidate was identified. All faint sources found in the vicinity of the central star are presumably background stars. A detailed estimate of the detection limit in 28 of the observed targets was obtained and it is described in details in Masciadri et al. (2004). This permitted us to calculate the typical contrast ($\Delta M$) between a planet and a central star at $0\farcs5$ and $1''$ provided by NACO for a typical integration time of 20-30 min (see Section 2) and to present a statistical analysis of the upper limit for the star/planet separation (Fig.1-Left and Table1).

Our most relevant result is that, in our sample of targets, in 100% of cases, no $10M_J$ (and more massive) exo-planets was detected at distances larger than 36 AU and no $5M_J$ (and more massive) exo-planets was detected at distances larger than 65 AU. If one considers the median values of the cumulative distributions we have that, in 50% of cases, no $10M_J$ (and more massive) exo-planets should exist at distances larger than 8.5 AU and no $5M_J$ (and more massive) exo-planets should exist at distances larger than 14 AU. We emphasize that, this statistical estimates, were done for the projected distance star/exo-planet. We are not considering here the possibility that planets might not be visible in part of their orbit. Our study indicate that massive planets are rare at distances larger than 6 AU as well as at distances smaller than 6 AU as indicated by radial velocity estimates (see Section 2).

We underline that for the category of massive, warm and self-luminous planets that we looked for in our survey, it is not possible to calculate a reliable probability distribution for detecting planets. The reason is that, to do this, one should need to know the planet frequency distribution *'a posteriori'*. This is obviously impossible to do if no-planets have already been detected. For this category of planets, one can only define some merit functions (depending on several parameters such as the age, the distance from the observer, the magnitude of the central star, the mass of the planet) to define some criteria to select targets for which the detection should be particularly favourable. For this reason, we think that it is fundamental to report results (even of non-detections) for the category of exo-planets that we are searching for and to try to get a homogeneous analysis as possible of the results in order to improve the statistics of the upper limit for star/planet distance.

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