Giant planets in debris disks around nearby stars
- A large NaCo L′-band imaging survey -

Abstract

We propose to conduct a large NaCo L'-band coronographic AO angular differential imaging survey of a statistically significant sample of ≈180 young and nearby A4 – G5 stars with debris disks. The main scientific aim of this survey is the revelation and characterization of the theoretically hypothesized but largely unknown wide-separation (>10 au) planet population that may originate from a mix of in-situ formation and early dynamical evolution. Our survey will be partially overlapping, but also complementary to other state-of-the-art large exoplanet imaging surveys, like with SPHERE or GPI, since it will cover a different parameter range by exploiting the L'-band sensitivity to lower-mass and older planets and target a wider age range. The particular power of the proposed survey derives from this complementarity, the focus on stars with known and well-characterized debris disks (as robust tracers of planet formation), and the combination of restricting the stellar mass range and taking very deep images of a large, statistically significant sample. The completion of the proposed survey requires ≈120 UT nights with NaCo, distributed over 3 or more years.

1 Scientific Rationale

The discovery of planets orbiting main-sequence stars other than our Sun captures the interest of both scientists and the public with the prospect of finding life elsewhere in the Universe. Since the first discovery in 1995 [15], we have gained a wealth of information to understand the formation and structure of planetary systems, including our own. With more than 1500 confirmed exoplanet discoveries by now, we have not only learned that the diversity of planetary systems is much larger than what one could guess when extrapolating from our own solar system, but we also start to gain statistical evidence on how the planet formation process acts under different conditions.

The most successful exoplanet discovery techniques thus far are the radial velocity (RV) method, which measures the radial component of the recoil motion of the host star from time series of high-resolution optical/NIR spectra, and transit surveys, both ground- and space-based. However, although very successful in terms of discoveries and providing good statistics, both methods have non-negligible detection biases and limitations such that important questions remain unanswered. Both are intrinsically biased toward short-period planets and both usually avoid young stars, because the spectroscopic and photometric variability of young and chromospherically active stars imposes major obstacles. Microlensing has similar limitations in terms of discovery probability and excludes the possibility of confirmations or follow-up studies. Astrometry, on the other hand, and in particular with the start of *Gaia* science operation, will provide us in the coming years with new discoveries that are expected to reveal the still incompletely known giant planet population in the 5 – 10 au separation range.

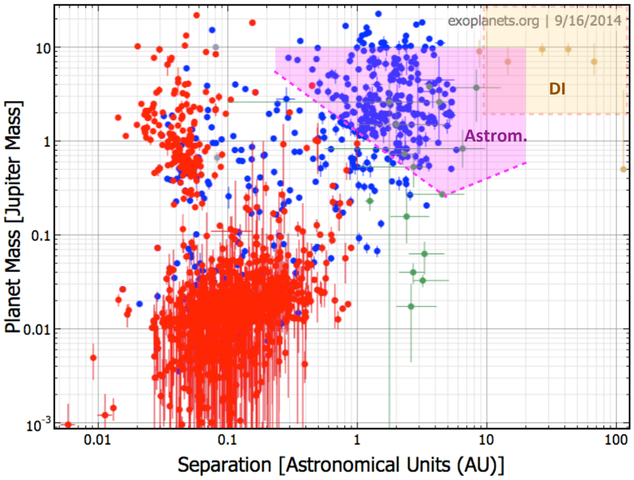

Figure 1: Distribution of planet masses vs. mean orbital separation of all known exoplanets as of 16 Sep 2014 [exoplanet.org]. Color coding reflects detection method: RV = blue, transit = red, microlensing = green, direct imaging = orange. The pale orange rectangle highlights the parameter space that will be explored by state-of-the-art direct imaging surveys like the one we propose. The magenta area marks the parameter space we anticipated to target with the original PRIMA-ESPRI astrometric survey [9], showing that the original ESPRI science and the imaging survey proposed here actually overlap in exoplanet parameter space.

Consequently, we still know very little about, e.g., the frequency of rocky (Earth-like) planets in the habitable zone around solar-type stars or the occurrence rate of giant planets at orbital separations beyond $\approx$ 10 au. Both would be important pieces of evidence that are ultimately needed when we want to constrain the uncertain ends in planet formation and evolution models (e.g., [3, 6, 16]). While the domain of rocky planets in the habitable zone is expected to open soon with the in-depth analysis of existing (e.g., from *Kepler*) and new transit data and progress in RV surveys, planets in very wide orbits have to be explored with direct detection techniques, mainly because of the long orbital time scales involved.

The occurrence rate of long-period giant planets is theoretically highly uncertain and observationally very poorly constrained. It is not only governed by the protoplanetary disk structure and planet formation process (e.g., core accretion vs. gravitational instability or alternative scenarios), but will also reflect dynamical re-structuring processes after planet formation. Both migration processes within the protoplanetary disk during the first 1 – 10 Myr, as well as dynamical interactions between planets well after the clearing of the disk can change dramatically the architecture of planetary systems between birth and maturity (like, e.g., the "grand tack" scenario for our own solar system). Hence, there is an explicit scientific demand to find and characterize giant exoplanets in wide orbits around young stars that cannot be satisfied by the successful indirect detection techniques mentioned above.

Direct imaging with extremely high-contrast techniques has already provided us with some spectacular discoveries in recent years (e.g., [7, 13, 8]), which proved that such planets exist and a dedicated survey would not conclude with a null result. However, the number of directly imaged planets is still very small and robust conclusions on the frequency and origin of such planets cannot be drawn yet. New-generation instruments like SPHERE at the ESO-VLT or the Gemini Planet Imager (GPI) have just started or will soon start to step by step fill this gap (see Fig. 1). However, these surveys mostly operate at NIR wavelengths between 1 and 2.2 μm and are thus optimized to detect hot (young and massive) planets (see next Section).

2 Immediate Objective

We propose to conduct a large NaCo L'-band coronographic AO angular differential imaging survey of a statistically significant sample of $\approx$150 nearby, roughly solar-type (A4 – G5) stars with debris disks to search for and characterize giant planets in wide (>10 au) orbits. The main scientific questions we want to address with this survey are: *(i)* How frequent are giant plants around solar-type stars at orbital separations beyond 10 au? *(ii)* What is the luminosity and separation distribution of such planets? *(iii)* Is the distant planet population dominated by in-situ formation or by outward scattering of planets formed further in? *(vi)* What is the relation between debris disk properties and the presence of wide-separation planets (constrain stirring models and establish debris disk properties as planet tracer)?

An important aspect of our survey is the focus on stars with known debris disks derived from the recently published "*Spitzer* IRS debris disk catalog" by [5], the first comprehensive debris disk catalog that uses spectroscopic data and attempts to characterize the dust belts in terms of temperature and separation from the star. In debris disks, the primordial (protoplanetary) dust has been processed completely and the current dust population is resulting from the collisional grinding of larger planetesimals. Hence, emission from debris dust around stars older than $\approx$10 Myr (the disk clearing time scale) is a consequence and thus a tracer of on-going planet formation. Moreover, the presence of large amounts of small and hot dust grains close to the star can theoretically not be explained even by large asteroid belts and self-stirring, but requires the presence of giant planets at a few tens of au from the star [21, 22, 11, 1].

Another specific aspect of our survey is that we want to obtain images in the L'-band at $\approx$3.8 μm. While other state-of-the-art instruments and surveys (e.g., SPHERE-NIRSUR or GPI) observe at shorter ($J - K$) wavelengths, our proposed NaCo L'-band survey will not only be complementary in providing color and temperature information for detections in common, but will actually be more sensitive to cooler planets. Figure 2 shows that the star – planet contrast in L-band is much more favorable than at shorter wavelengths (H and K-band), especially for older and lower-mass planets. E.g., for a 5 M_{Jup} planet around a 100 Myr old 1.5 $\mathrm{M}_{\odot}$ star, the L'-band contrast is 3 mag smaller than the H-band contrast. Note that the COND03 models [4, 3], on which these calculations are based,

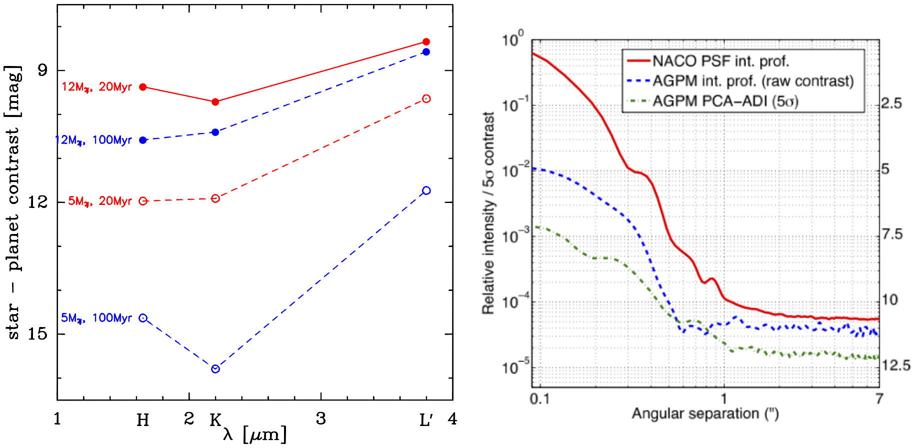

Figure 2: Left: Expected star–planet contrast for a 1.5 M$_\odot$ star, the 'typical' target of our survey (see Fig. 3) and two planets (5 and 12 $M_{\rm Jup}$) at two ages (20 and 100 Myr). The calculations are based on PMS stellar evolutionary tracks from [18] and the COND03 models [4, 3] for planetary atmospheres. Right: Normalized relative intensity profile and contrast curve derived by [14] for NaCo-AGPM-PCA-ADI with $t_{\rm int}$ = 800 s for a ≈6 mag star.

assume a 'hot start' for the planet formation. Newer models that also consider a 'cold start' scenario predict lower planet temperatures at early times (20 Myr to 1 Gyr, depending on planet mass) and hence an even larger contrast advantage at longer wavelengths [6, 16].

This tendency and large uncertainty in theoretical models underlines the usefulness and potential advantage of an L-band survey and the necessity of complementary L-band observations for surveys like SPHERE-NIRSUR or GPI. Furthermore, we will exploit the advantageous L'-band sensitivity to cooler planets by targeting a significantly wider age range than SPHERE-NIRSUR and GPI and taking very deep images of all target stars. Another, comparable large high-contrast L'-band survey is currently conducted at the LBT (LEECH [19]). However, target overlap with this northern hemisphere survey will be very small. Furthermore, LEECH targets primarily nearby intermediate age field stars (>100 Myr) not specifically selected for debris disks. The two surveys will therefore deliver statistics of complementary star sample and parameter ranges.

3 Source selection and target list

For our target candidate list, we select stars from the Spitzer IRS debris disk catalog of [5] with the following primary selection criteria:

- Debris disk signature with one or two dust components listed in [5]
- -70 deg $\leq$ DEC $\leq$ $+15$ deg ($>$ 4 hrs at AM $<$ 1.5)
- $K \leq 10$ mag (NaCo K-band WFS sensitivity)
- age $\leq$ 200 Myr (15 – 200 Myr; Fig. 3)
- Dist $\leq$ 200 pc (25 – 200 pc; Fig. 3)

With these primary selection criteria, we identify ≈ 200 target candidates from the Chen debris disk catalog [5]. About 50% of these stars were identified to have two detectable dust belts with one of them resembling warm zodi-like emission from small grains close to the star, which could indicate the presence of wide-separation giant planets [21, 22, 11, 1]. The large majority of target candidates is located at distances between 100 and 150 pc. Only about 20 target candidates are closer than 50 pc or further away than 150 pc. We will try to increase the number of very nearby stars (by 10 – 20) by exploiting other (smaller) surveys and may drop the most distant stars at d > 150 pc. Spectral types are mainly in the range G5 – A4 (≈ 0.9 − 2.2 M$_\odot$; Fig. 3). We may probably drop the few stars earlier than A2 from our list (small-number statistics). The final target list for our survey will then contain about 180 stars. About 50% of our selected targets are also in the SPHERE-NIRSUR target candidate list (mostly those with ages <20 Myr), i.e., these are the stars for which we will get the very valuable 2-color view. The other 50% will mostly probe slightly older stars where the L-band advantage does not only exploit planetary mass, but also age. Figure 3 shows the distribution of ages, distances, K-band stellar magnitudes, disk luminosities, stellar masses and spectral types for our pre-selected target sample.

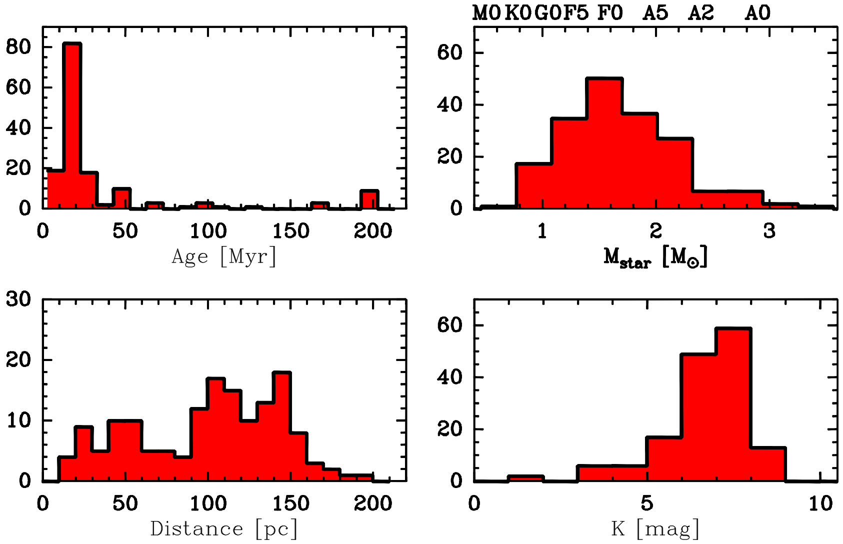

Figure 3: Distribution of ages, distances, K-band magnitudes, stellar masses and spectral types the preselected target stars.

Since most of our targets are located at distances between 100 and 150 pc, we will be mostly sensitive to giant planets at orbital separations >10–20 au, i.e. in a region that is not explored by RV or transit surveys (see Fig. 1). For a relatively small number of nearby targets (≈10–20) we will, however, be sensitive to giant planets close to the ice line, i.e., the suspected main planet formation zone. We estimate the approximate sensitivity of the proposed observations to planets around all selected target stars (considering their distances, masses, ages, spectral types, brightness, colors, etc.) as function of planetary mass, age, and separation by employing the COND03 models from [4, 3] and comparing the expected star – planet contrasts to the contrast curve derived by [14] for NaCo-AGPM-PCA-ADI for a ≈6 mag star under moderate weather conditions (applying a simplified scaling to $t_{\rm int}$ = 2.5 hrs and ΔPA=90deg). Figure 4 shows that we will be sensitive to 5 $M_{\rm Jup}$-mass planets around young 1 $M_\odot$ stars (20 Myr) down to the inner working angle (IWA; ≃ 10 au at 100 pc) and down to ≈ 0.3 – 0.4″ (≃ 35 au) around 2 $M_\odot$ stars. Older (100 Myr, cooler) planets can be detected at separations > 30 – 50 au. More massive planets (12 $M_{\rm Jup}$, young and old) can be detected down to ≈10 au around most stars with $M_* < 2\,M_\odot$.

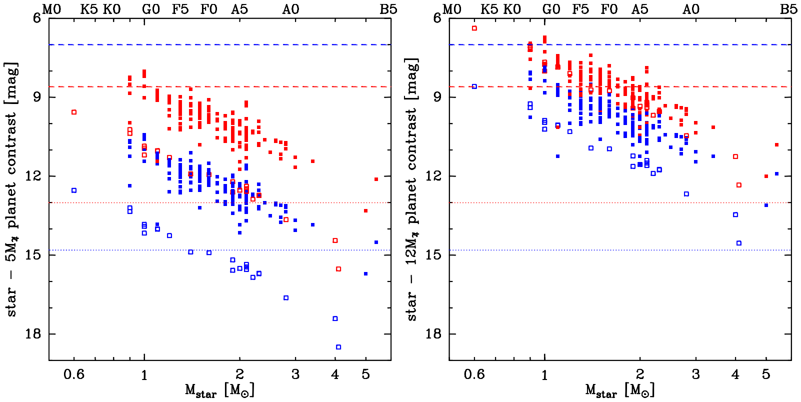

Figure 4: Expected star–planet contrast for all targets, assuming 5 $M_{\rm Jup}$ (left) and 12 $M_{\rm Jup}$ (right) companions, adopting the COND03 models [4, 3] for planetary luminosities and colors, and approximating ages <50 Myr to 20 Myr and > 50 Myr to 100 Myr. Red refers to L'-band, blue to H-band, full squares to 20 Myr and empty squares to 100 Myr. Dashed and dotted horizontal lines show the approximately achievable 5 σ contrast (±1 mag uncertainty) with 1 hr ADI on a 6 mag star close to the IWA and at 1″ for NaCo-AGPM (red, L'-band, [14]) and SPHERE-IRDIS (blue, H-band, [20] and ETC).

A comparison with the expected performance of SPHERE-IRDIS ([20] and SPHERE ETC) shows that at small separations, close to the IWA, the proposed NaCo L'-band observations will be more sensitive to lower-mass and older planets than SPHERE. At angular separations ≳ 0.2 – 0.3″, SPHERE will be sensitive to larger star – planet contrasts than NaCo. This is however compensated approximately by the lower intrinsic star – planet contrast at L-band as compared to H. Since this contrast does not only depend on mass and age, but also on the uncertain formation and evolution scenario (e.g., ’hot’ vs. ’cold start, see above), its prediction has large uncertainties and only the observations can show which band is better suited for the detection of what type of planets (apart from the tendencies mentioned above, which still hold). This means that for those ≈100 targets that may potentially overlap with SPHERE-NIRSUR, we will be able to provide a very valuable second color for nearly all SPHERE discoveries and may possibly detect additional planets. For the other ≈100 targets that will probably not be observed with SPHERE, which mostly have ages > 50 Myr, we will be able to probe the outer planet population down to smaller masses (hence statistically more detections) than SPHERE can do for the younger stars.

4 Observing strategy and time estimate

We propose to use the NaCo [10, 17] L27 camera with L' filter together with the annular groove phase mask (AGPM) vector vortex coronagraph [14] in pupil stabilized mode to carry out deep angular differential imaging (ADI) observations [12] of the complete sample of ≈180 nearby debris disk stars that are in reach of NaCo. To subtract the stellar point-spread function (PSF) from the sub-images, we will use the principal-component-analysis (PCA)-based package PYNPOINT [2]. In order to reach the anticipated sensitivity of $5-10\,\mathrm{M_{Jup}}$ (depending on spectral type, age, and distance), we require an average field rotation of $\gtrsim 90°$ and contrast inside $0.2''$ of $\Delta L' \gtrsim 9$ mag for a 6 mag (L') star. Both can be achieved for most of our targets with a total observing and integration time (overheads are very small) of 2.5 – 3 hrs (very few targets need 4 hrs, for some fast-rotating targets we may need to add up a few shorter observations). Considering overheads, e.g., for acquisition and astrometric calibration, we therefore estimate that we can obtain on average two observations per night. Observing all 180 stars once will thus require a total of 90 nights. Since we expect that about 30% of the stars will need a second epoch for candidate confirmation or rejection, the complete survey would require ≈120 nights. Any further down-scaling would compromise the statistical power of such a survey since we would loose the statistical significance along at least one of the two important parameter axes spectral type (stellar mass) and age.

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