OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jun **Proposal type:** short-term

Searching for planet c around GJ 504 with the new coronagraphic mode of LBTI/LMIRCAM

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Abstract of Scientific Justification

GJ 504 is a young and metal-rich sun-like star (G0V, 160^{+350}_{-60} Myr, 17.5 pc) surrounded by a four-Jupiter-mass planet very recently discovered by the $Subaru$ telescope. Explaining the wide orbit of this planet (43.5 AU) with the core accretion model of planet formation requires the presence of unseen massive planet(s) in the inner system (at a few AUs). This (these) planet(s) would be at the source of planet scattering processes. With this proposal, we intend to obtain unprecedented sensitivity to giant planets in the inner region of the GJ 504 planetary system using the new generation vortex coronagraph (AGPM) recently installed in LBTI/LMIRCam. This new mode of LMIRCAM is expected to provide high-contrast imaging down to an inner working angle of 0.″09 (1.5 AU at the distance of GJ 504) to go well below the current limit of 0.″3 with direct imaging using LBTI/LMIRCAM in the L band ($\sim$3.8 μm, a very favorable wavelength for exoplanet observations). Our goal is to look for a c component, or at least derive the tightest constraints ever put between 1.5 and 3 AU, down to $\sim$12 $M_{\rm Jup}$. In addition, the proposed observations will be used to continue the characterization and performance assessment of this new ground-breaking coronagraphic capability of LMIRCAM. We expect to demonstrate improved performances with respect to the direct imaging mode of LMIRCam and validate this new coronagraphic mode for the ongoing LBTI planet survey (LEECH, see companion proposal by A. Skemer).

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	LBT	LBTI	LMIRCAM	*		1.0	bright	Jan-Jun	Jan–Jun	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: For practical reasons, we would like the proposed observations to be scheduled with other LBTI observations.

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	GJ 504	13:16:46.52	+09:25:26.97	V=5.2, L'=3.94, G0V
2	HR 4960 (reference)	13:09:12.00	+10:01:21.00	V=5.8, L'=3.2, K0III

Approval for Instrument Use from PI: See general e-mail sent separately by P. Hinz to the TAC.

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

GJ 504 is a young and metal-rich sun-like star (G0V, 160^{+350}_{-60} Myr, 17.5 pc) surrounded by a Jupiter-like planet very recently discovered by the Subaru telescope (Kuzuhara et al. 2013, ApJ 774). GJ 504 b is the first wide-orbit giant planet detected around a metal-rich star, which is also the oldest among all stars harboring directly imaged planets. According to planet formation theories, the high metallicity of the host star may enhance massive planetary cores, while preventing the effective cooling of a protoplanetary disk, and thus be more hospitable for core-accretion and gravitational instability planet formations. Given its properties, the GJ 504 system may provide important clues to understand the formation and evolution of giant planets. Further observations are crucial in that respect.

Intriguingly, the core accretion model suggests the presence of unseen massive planets at small angular separations in order to explain the wide orbit of GJ 504 b (Nagasawa et al. 2008; Chatterjee et al. 2008). N-body simulations for the dynamically unstable gas-free planetary system predict that such inner companions should orbit at a few AU from the host and have masses equal or greater than the corresponding outer planets (Nagasawa et al. 2008; Chatterjee et al. 2008). Therefore, the inner counterpart of GJ 504 b would have to be more massive than $\sim$4 $\mathrm{M_{Jup}}$ if it exists, although radial velocity observations have found few planets in this mass range at semimajor axes of a few AU (Mayor et al. 2011) and the remaining gas in the disk may affect the scattering of planets, changing the congurations of planets predicted by the simulations for the gas-free cases (Moeckel & Armitage 2012). In addition to probing the inner planetary region, monitoring the orbit of the outer planet is also important, since scattered planets preferentially have high eccentricities (Chatterjee et al. 2008).

Our goal is straightforward. We want to image and constrain the inner regions of the GJ 504 planetary system like never before, using LBTI/LMIRCAM with the recently installed L-band Annular Groove Phase Mask vector vortex coronagraph (AGPM, Mawet et al. 2005, ApJ 633, 1191). Conversely to most coronagraphs, the LBTI/AGPM can detect faint sources as close as λ/D, providing an inner working angle of only 90 mas at L band, which will allow us to peer extremely close to the star (i.e., $\sim$1.5 AU). Using angular differential imaging (ADI), which is perfectly adapted to the symmetry of the AGPM, we recently demonstrated contrasts of $\Delta L \sim 8$ at 0.″1, and of $\sim \Delta$L >9 beyond 0.″2 with the AGPM-L4 installed in LMIRCAM (see Fig. 2 and Fig. 3). The rejection ratio of stellar flux for this first try is approximately 35

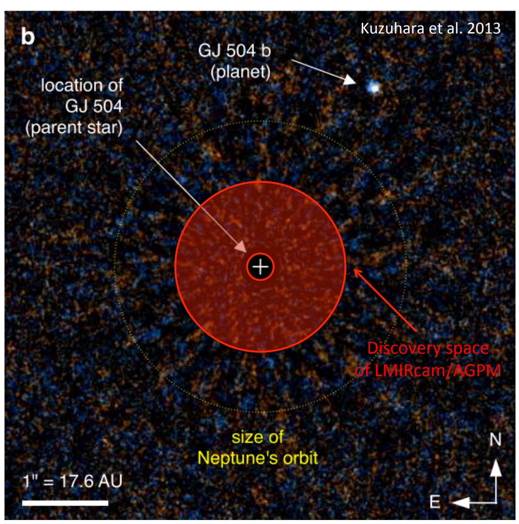

Figure 1: Exploring the inner planetary regions of GJ 504 with the AGPM vector vortex mask recently installed on LBTI/LMIRCAM. This new mode is expected to achieve an improved contrast compared to the direct imaging mode between 0.″09 (1.5 AU at the distance of GJ 504) and 1.″0 as shown in Fig. 2. This discovery space of LMIRCAM/AGPM is represented by the red-shaded area overplotted on the *Subaru* image (Kuzuhara et al. 2013).

which is far from optimal. Based on our experience with other telescopes, we estimate that we can reach a rejection ratio of 100 by fine tuning the alignment of the star behind the coronagraph and by a better optimization of the telescope focus. With these improvements, we expect to reach a contrast $\Delta L \sim$10 at $0\farcs1$. This would provide a benchmark data set in this wavelength range, and would rule out (or discover) any putative massive companion in the inner system (see Figures 1 and 2), potentially down to 5 M_J at 1.5 AU. Our team of experts possesses all the needed skills to carry out the coronagraphic observations, reduce the data, and perform the orbital element computations.

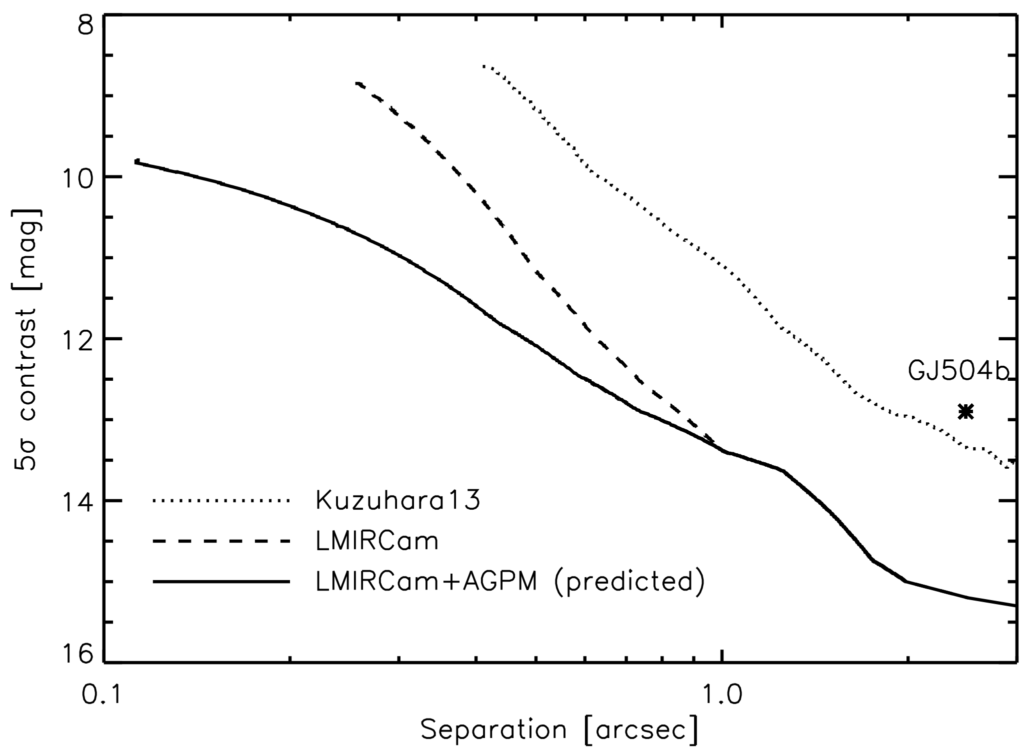

Figure 2: Contrast curve obtained with *Subaru* (dotted line, Kuzuharu et al. 2013) compared to the one obtained with LBTI/LMIRCAM in direct imaging mode (dashed line, Skemer et al., in prep). The AGPM coronagraphic imaging will open a new parameter space around GJ 504 (see solid line), enabling us to study the inner region down to $0\farcs09$ with a contrast of 10-13 magnitudes as extrapolated from NACO AGPM-L3 observations (Mawet et al. 2013, Absil et al., submitted). According to laboratory measurements, the AGPM-L4 installed on LBTI/LMIRCAM is the best AGPM manufactured so far and, combined to the new-generation AO system available at the LBT, the proposed observations will provide the best contrast/resolution worldwide at L band.

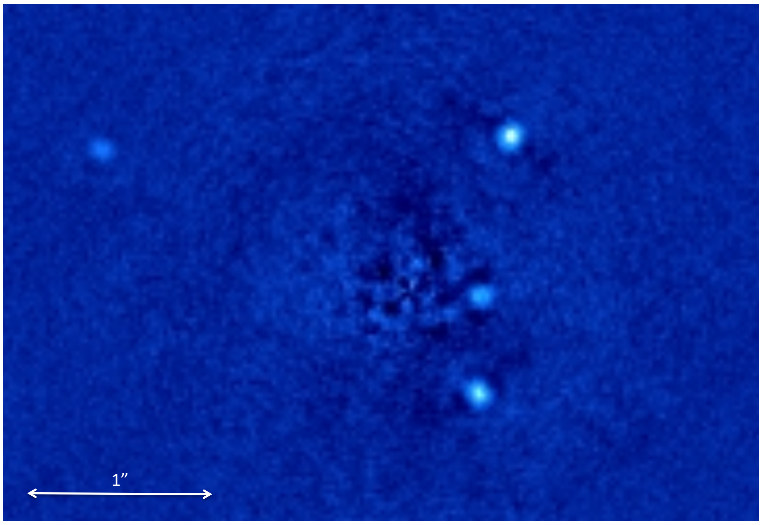

Figure 3: First L'-band coronagraphic image (linear scale) obtained with LMIRCAM/AGPM on 2013 October 17th (Defrère et al. 2014). The four known planets around HR 8799 are all detected clearly at high SNR and the contrast achieved near the star ($<0.''3$ or $\sim$10 AU at the distance of HR8799) is the best ever at L'. The central star has been subtracted by the AGPM coronagraph and image processing.

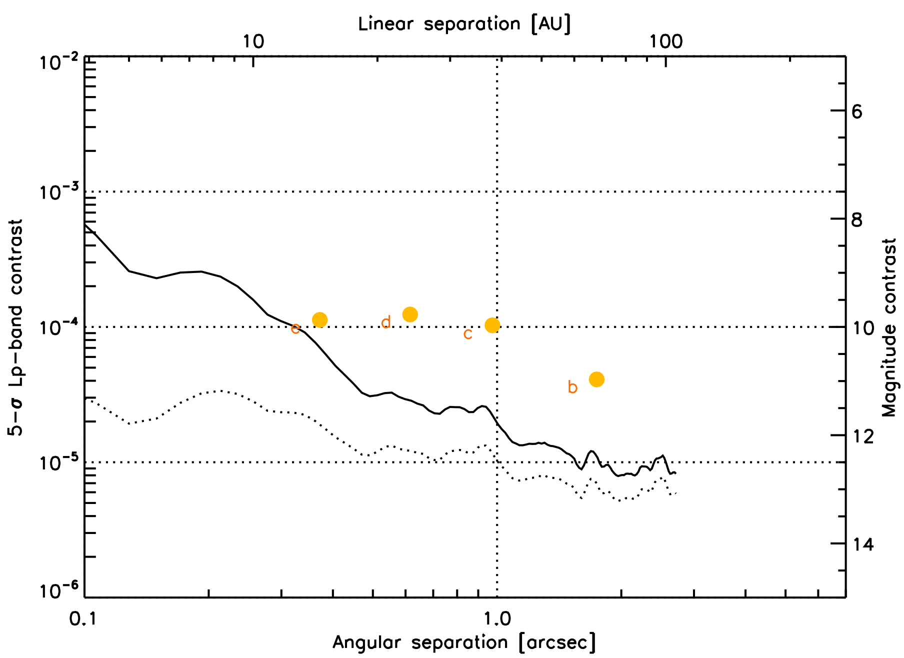

Figure 4: Current 5-σ detectability of LMIRCAM/AGPM in terms of contrast for point-like companions around HR8799 (solid line). The dotted line represents the raw contrast curve (without considering self-subtraction). The four-known planets are shown for comparison (magnitude from Marois et al. 2008 and 2010). For this first try, the rejection ratio of the stellar flux was approximately 35 (far from optimal) and we expect to be able to reach 100 with the proposed observations (or $\Delta L \sim$10 at $0.''1$). This will open a completely new parameter space for high-contrast imaging with LBTI/LMIRCAM.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

The LBT/LMIRCAM observations will be carried out with the new coronagraphic mode in order to achieve high-contrast imaging down to the inner working angle of $0\farcs09$ ($\sim$1.5 AU at the distance of GJ 504) at L (3.8 μm), a sweet spot to image and characterize young extra-solar planets. Unlike the previous observations which were obtained with one telescope only (see Figures 3 and 4), the plan is to use the new double Lyot stop and precisely overlap the two beams on top of the AGPM center in order to get the sensitivity equivalent of a 12.5-m telescope. The differential tip/tilt between the beams will be corrected by LBTI's tip/tilt sensor which works routinely now. In addition, we plan to use a new automatic script to precisely align the star with the center of the AGPM and optimize the focus of the telescopes. The latter is expected to provide the main performance improvement of the coronagraph. Angular differential imaging will be used to enhance the contrast delivered by the AGPM coronagraph.

Our integration times will be as short as possible (to take out residual tip-tilt power) while maintaining maximum efficiency (i.e. filling the detector wells and limiting read overheads, which are currently 0.3 seconds per frame). This will probably lead us to integrate for 1.5 seconds, unless we are able to lower the read overhead. In order to maximize parallactic angle rotation, GJ 504 will be observed for about four hours around transit, allowing 90 degrees of parallactic angle rotation. In principle, this is sufficient to detect companions down to the inner working angle of the AGPM. However, at very small angles, exoplanets do not azimuthally move fast enough to avoid self-subtraction with ADI. Indeed, field rotation in terms of resolution elements (λ/D) becomes too slow, and yields a very bad efficiency in terms of speckle decorrelation vs self-subtraction at small angles.

To alleviate this drawback, we plan to perform reference star differential imaging (RDI), a technique well-known by our team and which already demonstrated contrasts of $\sim \Delta$Ks > 11 at an angular distance of $2\lambda/D$ a few years ago with a liquid-cristal vortex coronagraph installed at Palomar (Serabyn et al. 2010, Nature 464, 1018). In practice, we plan to observe the carefully-chosen reference star every 15 minutes, during the 4-hour ADI sequence. This matches the typical recentering cadence for the star under the AGPM mask (from our experience on VLT/NACO).

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

So far, 1.5 night has been allocated to the current project (1 night in 2013B and 0.5 night in 2014A). In 2013B, 0.5 night was used to get the data presented in Figures 3 and 4 (Defrère et al. 2014) and the other half night was lost because of bad weather conditions. The 2014A half-night dedicated to GJ 504 was also lost because of bad weather conditions. This time, we ask for one night in order to have enough time to fine tune the new automatic scripts to precisely align the star with the center of the AGPM and optimize the focus of the telescopes. Based on our previous experience, we estimate that 4 hours of engineering will be necessary to achieve a rejection ratio of at least 100 and be ready for the science observations. We estimate that approximately 4 hours of observations around transit will be necessary in order to reach the sensitivity required to look for a second planet companion in the inner region around GJ 504 and to validate the performance of the AGPM in terms of contrast at small angular separations. The AGPM is expected to open a completely new parameter space for LBTI/LMIRCAM (gain in contrast and spatial resolution, see Figures 1 and 2) at a wavelength (L-band) which is a sweet spot to image and characterize young extra-solar planets.

Follow-up observations will be needed only in case of a (tentative) detection of GJ 504 c.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). **(up to one page)***

The PI and co-Is whose name is underlined on the first page have all been using Steward facilities (and particularly the LBTI) on a regular basis over the last 2 years. In particular, several papers using LBTI/LMIRCAM observations have been published recently (e.g., Rodigas et al. 2012, Skemer et al. 2012, Bailey et al. 2013, Bonnefoy et al., 2013, Skemer et al. 2014) and many other are under preparation. In addition to the allocated time listed in the previous section, the PI of this proposal has also been allocated 2 nights for L-band interferometric imaging of nearby hot exozodiacal dust systems with LBTI/LMIRCAM. The first night was lost due problems with the DX secondary mirror and the second night was lost because of bad weather conditions.