OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** short-term

Characterization of the First Directly Imaged Forming Planets: The GAPlanet Survey (Finishing the First Epoch Survey)

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Abstract of Scientific Justification

We propose second epoch follow-up for two of our Key "fall" targets (and 4 first epoch observations) for the Giant Accreting ProtoPlanet Survey (GAPplanetS), the highly productive "key project" devised by the MagAO team. Specifically, we propose to finally *finish* mapping the first epoch sample of all 16 bright southern transitional disks at $\sim$ 20mas in Hα with the, newly improved, Spectral Differential Imaging (SDI) mode of the VisAO camera. This SDI technique for detecting young accreting point sources and for probing disk structures on small spatial scales is a unique capability of MagAO (Close et al. 2014). It allows us to "catch" protoplanets during the epoch of formation/accretion of disk material inside of transitional disk gaps by isolating Hα emitting point sources at very high contrast and tight separation. In particular, we detected in our 2014B "fall" sample a beautiful 5σ Hα detection of the first true accreting protoplanet (Sallum et al. NATURE in prep). Here we request follow-up observations of this amazing young planet. These observations will give us a critical second look at this protoplanet's Hα accretion, and our first estimate of its Brγ strength, dust extinction, and orbit. We also request 4 first epoch observations of important GAPplanetS survey targets. These observations will go a long way toward informing the debate on whether planet formation is the dominant mechanism for creating transitional disk clearings. The small inner working angle and high spatial resolution of MagAO will allow us to probe closer to the star (<10AU) and at higher resolution than previous direct imaging studies, opening new and exciting regions of exoplanet parameter space. With these 2015B observations we will have finished all first epoch observations required by the GAPplanetS survey, leaving only a few 2nd epoch observations remaining.

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	MAG2	AO	VisAO & Clio2	*	*	3.0	any	Nov	Nov-Dec	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: Must be part of the Nov-Dec MagAO 2015B run. It would also be best to be six second half nights if possible. If it must be full nights please schedule the last three nights of the run (Dec 17,18,19) as they are the best for these particular target RAs.

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	V1247 Ori	05:38:05.25	-01:15:21.7	R=9.7, R_{cav}=120mas, 2nd epoch follow-up
2	LkCa 15	04:39:17.8	+22:21:03.5	R=11.6, R_{cav}=360 mas;Proto-Planet 95mas, Follow-up
3	UX Tau A	04:30:04.0	+18:13:49.4	R=10.7, R_{cav}=180mas, first epoch
4	MWC 758	05 30 27.53	+25 19 57.08	R=8.3, R_{cav}=500mas, disk spiral arms, first epoch
5	AB Aur	04 55 45.84	+30 33 04.28	R=8.3, R_{cav}=600mas, disk spiral arms, first epoch
6	HL Tau	04 31 38.43	+18 13 57.7	R=14, R_{cav}=700mas, 4 gaps!, first epoch

Approval for Instrument Use from PI: _____

*(have instrument PI signature appear on, or attach PI e-mail to, **all** copies)*

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
Steph Sallum	Josh Eisner		no	yes

Scientific Justification

As the field of exoplanetary astronomy grows, some of the most pressing unanswered questions are where, how, and from what material do planets form around young stars. Young stars are surrounded by material left over from their formation that has settled into a thick disk of gas and dust called a protoplanetary disk. Many other young star systems, particularly in older star forming regions, host less massive disks of tenuous dusty debris, called debris disks. By studying systems that host disks, and in particular those most likely to also host young planets, we can begin to answer these questions. It is believed that protoplanetary disks become debris disks through an evolutionary process in which gas and dust is dispersed and/or incorporated into forming planets, clearing out the thick disks of material. This clearing process reduces the disk mass from a few Jupiter masses for protoplanetary disks (Taurus median $\sim$5x10^{-3} M$\odot$, Andrews & Williams (2005)) to fractions of an earth mass for debris disks ($\sim$0.001-0.1M$\oplus$, Panić et al. (2013)). However, it is still unclear precisely how one type of system becomes the other.

Even among the small number of resolved disks, there is a wide range in their sizes, morphologies and compositions. The extent to which these variations are evolutionary, and what physical processes in the disk drive this evolution, is unknown. Competing, though in some cases complementary theories include: (1) Photoevaporation. High-energy light emitted from the young star serves to blow gas and dust out of the system (e.g Pascucci & Sterzik, 2009). (2) Grain growth. Primordial dust grains collide, coagulate and grow to larger sizes, making them both more difficult to detect and more difficult to drive out of the system through photoevaporation (e.g. Birnstiel et al., 2012; Dullemond & Dominik, 2005). (3) Planet formation. As planets form, they sweep up material within their range of gravitational influence, clearing the disk around them (e.g. Dodson-Robinson & Salyk, 2011; Zhu et al., 2011).

All of these processes are strongest in the innermost part of the disk, which is precisely the region that is the most difficult to study. This difficulty is due to the high resolutions required to resolve the inner disk, as well as the effect of residual starlight, which must be robustly removed to study the disk.

A subclass of disks termed transitional disks is a particularly relevant population to study in the context of disk evolution because transitional disks appear to be, as their name suggests, in transition between a young, gas-rich protoplanetary disk phase and an older gas-poor debris disk phase. In recent years, technological advancements have allowed us to resolve cleared inner gaps in many transitional disks. Most of these observations have been done either in the sub-mm regime through large radio interferometers (e.g Andrews et al., 2011, 2010) or in the near infrared (through adaptive optics (AO) technology (e.g Mayama et al., 2012; Thalmann et al., 2010). In some instances, these disks have been imaged at both wavelengths, and the stories told by the two are not always consistent.

MagAO, and in particular its visible light camera VisAO in Simultaneous Differential Imaging (SDI) mode (newly updated with all new single substrate "no-ghost" narrow-band filters) has the potential to open a new frontier in the study of transitional disks. It operates through a Wollaston Prism that is placed in the VisAO beam and functions as a 50/50 beamsplitter for unpolarized sources. Each half of the beam is passed through a different narrowband filter, one on a spectral line of interest and one on the neighboring continuum . The continuum channel functions as a simultaneous probe of the point-spread function (PSF) of the object of interest at a nearly identical wavelength, making subtraction and removal of continuum emission remarkably simple! **The robustness of SDI-mode PSF subtraction allows us to probe the disk closer to the central star (r$\sim$50mas) than can be achieved by any other AO imager**, and the visible (shorter) wavelength regime allows for higher diffraction-limited resolutions than are available elsewhere (Close et al., 2013). This opens up a window into disk regions that have previously been accessible only through interferometry, and never at visible wavelengths.

A second result published (and now widely cited) in (Close et al., 2014), demonstrates the power of this SDI $H\alpha$ observing mode inside of disk clearings. In March 2013, we imaged the transitional disk HD142527 in Hα SDI mode and were able to verify the existence of a previously disputed companion embedded inside the disk gap at just 86$\pm$3mas (12 AU). This companion was previously inferred interferometrically (Biller et al., 2012), however MagAO is the first system capable of directly imaging the object. The planet-star contrast at Hα is nearly three times that at the continuum (Δmag=8.5$\pm$0.1 vs Δmag=9.6$\pm$0.15), demonstrating that accreting objects like this one have much more favorable planet/star contrast ratios at Hα than at other wavelengths. Based on (a) the performance of the system, (b) the accretion luminosity of this object, (c) theoretical predictions that gas is funneled through transitional disk gaps in accretion streamers

that interact with planets (Dodson-Robinson & Salyk, 2011) , and (d) recent observations supporting the existence of these streamers (Casassus et al., 2013), we estimate that we should be able to detect accreting protoplanets with masses as low as 0.5MJup and at separations as tight as $\sim$ 50mas (5-10 AU).

This mass and separation regime is interesting because it corresponds to planets similar to the gas giants we see in our own solar system, a regime that has been inaccessible to the direct imaging technique until now. It also allows us to isolate objects at a key time in the coevolution of planets and disks, as disk material is being swept up and accreted onto forming protoplanets. Only 1 planet candidate had been previously been detected (and not directly) inside of a transitional disk gap (Kraus & Ireland, 2012, LkCa15b). So in the just completed 2014B season we attempted our first "fall" GAPplanetS run, and LkCa 15 was a prime target. Due to the El Nino weather pattern the fall run was mostly lost to uncharacteristically cloudy weather with poor seeing. Nevertheless, we did obtain an excellent 3hr LkCa 15 Hα SDI dataset. The main results of which are highlighted in figures 1 and 2. As is clearly shown in these very exciting images there is a bright accreting source in Hα that has no continuum counterpart (unlike HD142527B) hence, we know immediately that this a very low mass (likely planetary mass) accreting proto-planet. Moreover, nearly simultaneous images using the LBT NRM interferometric imaging detected a very red Ks-L' object consistent with our SDI Hα position. The colors of this object are best fit with a model of magnetospheric accretion luminosity not a photosphere (Zhu et al. 2015; Eisner 2015). Not only are figures 1 and 2 our first direct images of an accreting protoplanet, but they are also the first evidence that planets have significant magnetic fields to generate this much Hα accretion luminosity.

There is another planet in the gap (LkCa 15c; not detected in Hα but seen at Ks, and L' at Keck and LBT in NRM imaging; Sallum et al. 2015). LkCa 15 c has moved in the last 5 years on circular Keplarian orbit consistent with $\sim$10 AU, whereas b is consistent with a $\sim$12 AU circular orbit (fig. 2). Since the tidal radius (or Hill radius) is 1.2AU for a 5Mjup planet at 10 AU then both b and c are just outside of each others Hill radius if they have masses of < 4 Mjup. On the other hand, if they were both just above planetary mass (say 15 Mjup each) then their Hill radii (1.7AU for c and 2.1AU for b) would then badly overlap and the observed orbits would be unstable in much less than 1000 years (Dodson-Robinson & Salyk 2011). Hence we have both a spectral and a dynamical argument that the masses of both LkCa15 b and c are planetary, and likely both less than 4 Mjup.

So LkCa 15 b is a great example of a planet carving a gap in transitional disks. There should be many more for us to find (indeed we have already seen point masses in our HD142527, and HD169142 gaps images). No other currently operating AO systems are capable of imaging planets at such low masses and at such tight separations. This is due to the resolution advantage offered by a visible wavelength AO system and the additional Hα luminosity of accreting objects, which makes the planet-star contrast at this wavelength much more ($> 1000x$) favorable for detection (Close et al. 2014).

We propose here to carry out a second set (second epoch) of observations on LkCa 15b and V1247 Ori and new observations (first epoch) of the last 4 other GAPplanetS targets in our target list (all in MagAO's SDI mode).

The optical design of MagAO allows VisAO and the NIR camera Clio2 to operate simultaneously. This means that whenever we are collecting optical SDI data for this campaign, we are also collecting NIR data 'for free'. Although Clio2 does not have an SDI mode, traditional PSF subtraction as well as Angular Differential Imaging (Marois et al., 2008, ADI) techniques coupled with our new vector APPs (vAPP coronagraph) can be used to isolate disk and point source emission, respectively. We will focus on a point source search at L' band (3.9μm), which corresponds to the NIR wavelength at which planet-star contrasts are the most favorable for exoplanet detection (Burrows et al., 1997). This is also true in the case of magnetospheric accretion luminosity (Zhu et al. 2015; Eisner 2015). To have the smallest coronagraphic IWA we'll utilize the new vAPPs of Clio to resolve LkCa15b at 90mas at Brγ and 100mas at 3.9μm for all other targets.

References

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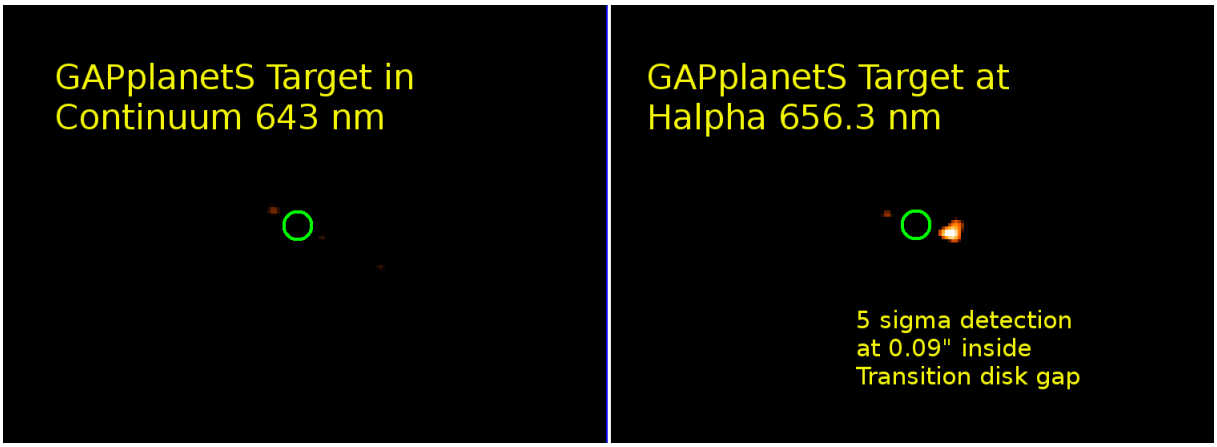

Figure 1: MagAO GAPplanetS Hα SDI detection of an accreting protoplanet (LkCa 15 b) in the LkCa 15 transitional disk gap (3 hour integration). We know it is very low mass due to a complete lack of continuum emission at 643 nm. LkCa15 c is not detcted due to, perhaps, a lower accretion rate.

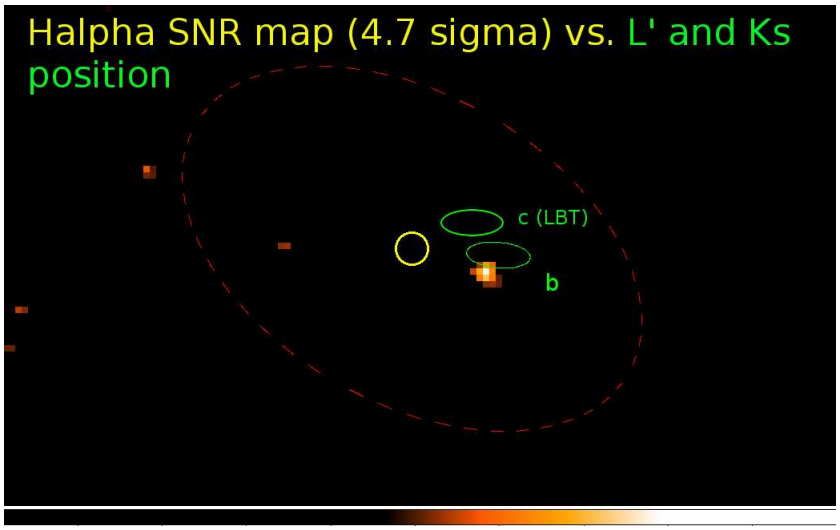

Figure 2: MagAO GAPplanetS SNR image from 2014B of LkCa 15 b. Note the detection of a very strong (4.7 sigma) Hα source (LkCa 15 b) consistent with the Ks and L band position found by Sallum et al. (2015) at the LBT with NRM imaging (the lower green 2σ error ellipse). The dashed line is the outer edge of the disk gap. Together the nearly simultaneous GAPplanetS Hα, Ks-L' color and the non-detection at 643nm, J, and H strongly argue for magnetospheric accretion of hydrogen gas onto a giant planet in orbit around LkCa 15 on a Keplarian orbit at $\sim$ 12 AU (based on a 5 year baseline from re-reduced archival KECK NRM interferometry). **This is astronomy's first direct look at a forming and accreting planet and is a great milestone for the GAPplanetS survey**. The follow-up observations requested for 2015B will be critical to confirming our orbital solution. Moreover the proposed measurement of the Brγ strength of this accretion will allow the estimation of the l.o.s. dust extinction to the planet once Hα/Brγ is measured and compared to case-B recombination theory.

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)***

MagAO is the first telescope system capable of doing differential AO imaging at the short wavelength of the Hα emission line and is therefore the first telescope system capable of imaging accretion phenomena on small spatial scales. Transitional disks are ideal targets for an Hα direct imaging census because (a) the clearing of material in their inner regions means that relatively little intervening circumstellar material is present to attenuate emission from companions, (b) many transitional disks are still actively accreting, making the probability for accretion streamers and Hα-emitting objects high and (c) planet formation as a mechanism for creating these gaps is a prevalent but contested explanation, and a census of accreting objects housed inside transitional disk gaps will identify unequivocally systems in which this process is at work.

The disk targets in this sample were chosen according to the following criteria: (a) observable from the Las Campanas site, (b) nearby (d$<$250pc) (c) sufficiently bright R-band guide star magnitudes to achieve moderate Strehl Ratios in the visible (SR$>$10%), and (d) a resolved cavity with r$>$100mas.

A note on the planned follow-up observations of LkCa 15 b Although it will certainly be a difficult observation due to its relative faintness and higher airmass, neither is insurmountable (as definitively proved in our 2014B run; see figs 1 and 2 for proof). We believe that LkCa 15 b follow-up is the most important target for this program in 2015B, and so we will "mini-queue" our GAPplanetS nights to guarantee success.

Kraus & Ireland (2012) detected a LkCa 15 companion at $\sim$90mas, but the validity of this companion was heavily debated in the community. We now have a critically important paper in prep (Sallum et al. 2015) that will prove this proto planet is real and, show for the first time, is actively accreting.

However, we still need to prove our 12 AU circular orbital model is correct and we would like to try to image this system at Brγ so that we can measure the Hα to Brγ ratio to estimate the dust extinction to the accretion site via case-B recombination theory as was done, for example, in the case of the Herbig Ae/Be star R Mon (Close et al. 1997). So we need critical 2015B follow-up observations of LkCa 15 in 2015B.

To detect the 95mas separation companion at Brγ we plan to utilize the new (2015A) vAPP Clio coronagraph (purchased by Jared Males and Laird Close) and the new (2015A) Brγ filter purchased by Laird Close. Our vAPP contrast models show that the new vAPPs should allow the required 10^{-4} contrasts at 95mas to detect LkCa 15b at Brγ with our PCA data reduction pipeline (Males et al. 2014). So while we detect the companion at Hα with VisAO's SDI mode we will simultaneously be detecting it at Brγ with Clio2 with no extra telescope time needed.

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**)*

Based on our experience with many successful first epoch GAPplanetS observations, very good SDI data sets can be obtained in $\sim$180min (clock time; 150 min integrations), even for fainter targets than any in this sample (R$>$12). Therefore we request 3.0 hours per Hα observation (will yield $\sim$60 degrees of sky rotation for each target), plus 1 hour of overhead for target acquisition and setup. Large 60 degree sky rotations are critically important for ADI data reduction with our PCA pipeline (Males et al. 2014; Close et al. 2014), and these targets are closely spaced in RA (all in the north and with RA$\sim$4:30-5:40 hours), so one target each second half of a night is ideal. We will use any remaining time (near sunrise) to investigate the feasibility of using other SDI imaging filters to image these systems.

NOTE TO TAC: To be honest we cannot make much use of the first halves in the Nov 2015B MagAO run since our objects are all above 2 airmasses until midnight. So splitting the nights (with GAPplanetS in the second half) with other observers would be preferred if possible.

We therefore request total of 3 nights of time (hopefully as 6 second half nights), one second half night for each target in our Nov/Dec MagAO timeframe.

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 TAC has been supportive of this very unique and very important MagAO key GAPplanetS project. And we think the successes of the discovery of Hα object HD142527B (Close et al. 2014) and the first confirmed proto-planet images of LkCa 15 b (Sallum et al. 2015, in prep.) are already very exciting results.

A brief history of GAPplanetS is as follows. We completed preliminary "proof-of-concept" observations related to this campaign during the November-December 2012 and March-April 2013 MagAO commissioning runs.

We were granted the first TAC science time of two nights in 2014A to begin the survey and these nights were a great success with most of our spring targets all having good first epoch observations.

We were also granted 1.5 nights of time in 2014B to observe the B semester "fall" targets in the sample, however these observations were mired in poor "El Nino" weather and only the LkCa 15 b and V1247 Ori first epoch observations were completed. The LkCa 15 observations were a great success however, and shows the ability of MagAO to do Hα imaging even at high airmass and with fainter R=11.6 targets.

We have also a 3 night May 2015 run coming up to finish off the second epoch of our "spring" targets in 2015A. Assuming this 2015A run is a success, and we receive the time asked for here in 2015B, we should have enough data (to within 1-2 nights for 2016B 2nd epoch follow-up) to completely finish the GAPplanetS survey and publish the major Meta-Analysis paper with a definitive argument about the nature disk gaps and accreting proto-planets. So the first MagAO key project is almost finished!

⋆ Close, L.M. Follette, K. et al. "Discovery of Halpha emission from the Close Companion in the HD142527 Transitional Disk. ApJ Lett 781 L30 2014

⋆ Males, Close et al., 2014 ApJ 786 32 "Magellan Adaptive Optics first-light observations of the exoplanet *beta* Pic b. I. Direct imaging in the far-red optical with MagAO+VisAO and in the near-IR with NICI" arXiv:1403.0560

⋆ Sallum, et al. (2015) ApJ 801, 85 "New Spatially Resolved Observations of the T Cha Transition Disk and Constraints on the Previously Claimed Substellar Companion"

⋆ Wu, Y-L., Close, L.M. et al. (2015) ApJ 801, 4 "New Extinction and Mass Estimates from Optical Photometry of the Very Low Mass Brown Dwarf Companion CT Ch B with the Magellan AO System"

For more examples of published refereed results with VisAO and SDI results see:

⋆ Kopon, D., Close L.M. et al. Design, implementation, and on-sky performance of an advanced apochromatic triplet atmospheric dispersion corrector for the Magellan adaptive optics system and VisAO camera. PASP, 125, 966, 2013

⋆ Follette, K. B., Close, L.M. et al. The First Circumstellar Disk Imaged in Silhouette at Visible Wavelengths with Adaptive Optics : MagAO Imaging of Orion 218-534. ApJ, 775, L13, 2013

⋆ Close, L. M., Males, J., et al. Diffraction-limited Visible Light Images of Orion Trapezium Cluster With the Magellan Adaptive Secondary AO System (MagAO). ApJ, 774, 94, 2013

⋆ Wu, Y. L., Close, L.M. et al. High Resolution H alpha Images of the Binary Low-mass Proplyd LV 1 with the Magellan AO System. ApJ, 775, 45, 2013

⋆ Rodigas et al. 2014 "Polarized Light Imaging of the HD 142527 Transition Disk with the Gemini Planet Imager: Dust around the Close-in Companion". ApJ Lett 791 L37

⋆ Nielsen, E. et al. 2014 " The Gemini NICI Planet-Finding Campaign: The Orbit of the Young Exoplanet beta Pictoris b", ApJ 2014 in press eprint arXiv:1403.7195

For published refereed examples of Clio2 high contrast imaging see:

⋆ Morzinski et al., in prep. "Magellan AO First-Light Observations of Beta Pictoris b. II. High-contrast imaging at 25um with MagAO/Clio"

⋆ Bailey et al. "HD 106906 b: A Planetary-mass Companion Outside a Massive Debris Disk" 2014 ApJ Lett 780 L4

⋆ Skemer, et al. (2014) ApJ 792, 17 "Directly Imaged L-T Transition Exoplanets in the Mid-Infrared" arXiv:1311.2085

⋆ Biller, et al. (2014) ApJ Lett 792, L22 "An Enigmatic Point-like Feature within the HD 169142 Transitional Disk" arXiv:1408.0794