OBSERVING REQUEST

University of Arizona Observatories

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

Filling in the Gaps: The GAPlanet Survey (MagAO Key Project)

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CoI(s): Laird Close (SO), Jared Males (SO)

Abstract of Scientific Justification

We propose to finish our spring sample and complete followup observations of point source candidates for the Giant Accreting Protoplanet Survey (GAPlanetS), one of a small number of "key projects" devised by the MagAO team. Specifically, we propose to map a sample of transitional disks at high spatial resolution (20mas) in Hα with the Spectral Differential Imaging (SDI) mode of the VisAO camera. This technique for detecting young accreting point sources and for probing disk structures on small spatial scales is a unique capability of Magellan AO. It will allow 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. 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 and at higher resolution than previous direct imaging studies, opening new and exciting regions of parameter space. In particular, the MagAO Hα SDI mode is capable of directly imaging protoplanets at lower masses and tighter separations than has been possible with any previous survey.

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	any	Apr-June	March-June	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*:

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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	HD 150193A	16:40:17.92	-23:53:45.2	R=8.4, R_{dip}=533mas
2	CS Cha	11:02:24.91	-77:33:35.7	R=10.8, R_{cav}=269 mas
3	HD 100546*	11:33:25.44	-70:11:41.2	R=6.7, R_{cav}=134mas
4	HD 169142*	18:24:29.78	-29:46:49.4	R=8.2, R_{cav}=159mas
5	HD 142527*	15:56:41.89	-42:19:23.3	R=8.3, R_{cav}=565mas
6	V4046 Sgr*	18:14:10.46	-32:47:34.5	R=10.2, R_{cav}=179mas

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
K. Follette	L. Close		no	no

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.

For example, the transitional disk SR21 has been shown to host a large (r$\sim$36AU) heavily-depleted inner clearing in the sub-mm (Andrews et al., 2011). However, 1.6μm near infrared (NIR, 1-5μm) images show no evidence of a cavity (Follette et al., 2013b). Many other disks (Dong et al., 2012, e.g) reveal similar morphological discrepancies at different wavelengths. Any model that purports to explain the mechanism through which these clearings are generated must be able to explain differences in the observed distribution of grains at varied wavelengths. Multiwavelength high-resolution imaging of transitional disks is thus essential in order to understand the exact mechanism that is responsible for clearing them.

MagAO, and in particular its visible light camera VisAO in Simultaneous Differential Imaging (SDI) mode 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 80mas) than can be achieved by any other AO imager, and the visible wavelength regime allows for higher resolutions than are available elsewhere. This opens up a window into disk regions that have previously been accessible only through interferometry, and never at visible wavelengths. There are currently three SDI filter sets (Hα, [OI] and [SII]), each of which provides a unique view on a particular process believed to occur in transitional disks.

The Hα SDI mode has been extensively tested on sky, and several cutting-edge results have already emerged.For example, I led a campaign to image the silhouette disk Orion 218-354 at Hα in December 2012 as part of an effort to characterize system performance on faint guide stars. The unique nature of this disk allowed us to probe the distribution of primordial interstellar medium-like grains by tracking the degree of attenuation of background nebular Hα emission at different locations in the disk. We found that the total mass in small dust grains represents a surprisingly small proportion of the total disk mass. This result hints that grains may grow to sizes that make them undetectable at Hα much more quickly than is generally believed. Full details of the result can be found in Follette et al. (2013a).

The aspects of the Orion 218-354 observations most relevant to this proposal are the technical innovations that were demonstrated, namely (a) that even with faint (R 12) guide stars, the performance of MagAO gives an order of magnitude improvement over seeing-limited imaging in the stellar FWHM and (b) that SDI mode PSF subtraction offers significant improvement over traditional PSF subtraction, allowing us to probe much closer to the star ($0\farcs1$) than was possible with other imagers, including the Hubble Space Telescope.

The first GAPlanetS result was published in (Close et al., 2014) and it demonstrates the power of this 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 83.1mas (12 AU). This companion was previously inferred interferometricaly (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$0.1 vs δmag=9.65$\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 0.5MJupiter and at separations as tight as 80mas.

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 has previously been detected (and not directly) inside of a transitional disk gap (Kraus & Ireland, 2012, LkCa15b), but if the prevailing theories for the formation of these gaps is correct, there should be many more for us to find. 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 favorable for detection.

We propose here to carry out a third set of observations in a survey of transitional disks in MagAO's SDI mode - a campaign that we're calling the Giant Accreting Protoplanet Survey (GAPlanetS). As such, we will focus primarily of a search for companions with the Hα filter set, but would also like to take a small amount of data using the [OI] and [SII] SDI filter sets in order to better understand whether they can be used to conduct complimentary observations of disk structures at high resolutions. This will help to inform future proposals related to this campaign.

In this iteration, we would like to complete our sample by observing the two remaining A semester objects - HD150193A and CS Cha - and complete followup of point sources and intriguing disk structures that were discovered in our 2014A data. In particular, we have several promising point source candidates to follow up. One of them (labeled point source 2 in the figure) is present in both the H-alpha and continuum filters, which hints that it may be a background object, however it is at the location of a planet candidate identified spectroscopically. Other point source candidates are present in the H-alpha filter alone, as expected for accreting protoplanets. These may well be out first true detected GAPlanetS, however as the SNR of these detections is marginal ($\sim$3-5 sigma), an additional epoch will aid greatly in lending their identification credence for publication.

We also identified several persistent artifacts in PCA data reduction procedures that resemble credible disk structures. We fear that these may be polarized artifacts induced as a result of the Wollaston prism used to split our beam, however we are generally able to remove these artifacts through either (a) examining which structures persist when using the continuum channel, the H-alpha channel or both as PSF references or (b) unsharp masking. We have been working to characterize these residuals, and feel that several may

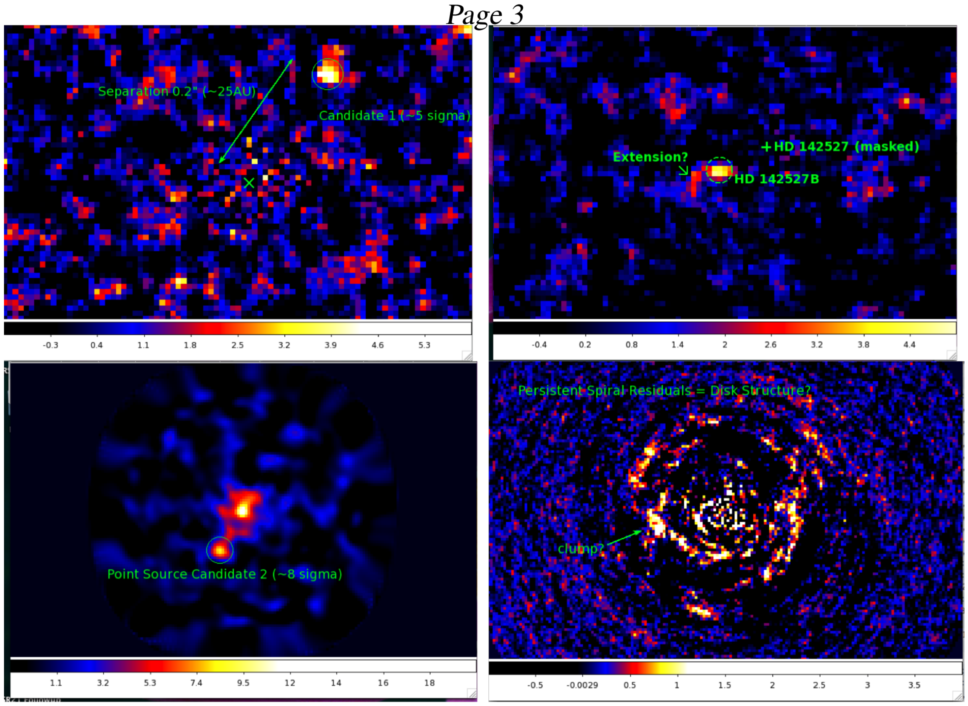

Figure 1: A sample of 2014A MagAO Hα SDI images of GAPlanetS targets that are worthy of followup because of either hints of disk structure or yet to be verified point source detections.

be real and warrant followup. If they are polarized artifacts, they should appear significantly different in a second epoch, while true disk structures will remain the same. If they prove to be real, these structures will be some of the smallest inner working angle disk observations to date.

Finally, recent GPI data of HD142527B, the object that we imaged as our first GAPlanet, revealed that there may be some circumsecondary material offset from the HD142527B point source (Rodigas et al., 2014). There are still some open questions about GPI astrometric calibrations, and it will be important to verify this finding with another telescope and instrument. We completed followup observations of this object in 2014A and find that our data reveal a hint of extension in the source that warrants followup. The highly improved H-alpha filter set also allowed us to probe much deeper than our initial observation and we have another fainter point source candidate to follow up in this disk as well.

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 can be used to isolate disk and point source emission, respectively. We will focus on a point source search at L’ band (3.8μm), which corresponds to the NIR wavelength at which planet-star contrasts are the most favorable for exoplanet detection (Burrows et al., 1997). For sources where extensive searches have already been done at this wavelength, we will conduct J, H or K band observations and attempt PSF subtraction to get a picture of the disk at NIR wavelengths. NIR emission at these wavelengths traces scattered light from small grains in the disk, and is an interesting contrast to optical observations.

References

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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.

Followup targets were chosen through reduction of our 2014A GAPlanetS data.

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 commissioning the system, very good SDI data sets can be obtained in $<$90min, even for fainter targets than any in this sample (R$>$12). We request 2 hours per Hα observation, plus 1 hour of overhead for target acquisition and setup. Large rotations are important for ADI data reduction, but the targets are sufficiently separated in RA space to allow for observation of two targets per night. We will use any remaining time to investigate the feasibility of using other SDI imaging filters to image these systems.

We therefore request 3 total nights of time, one half night for each of our 6 targets (2 new, 4 followup).

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**)*

We completed preliminary observations related to this campaign during the November-December 2012 and March-April 2013 MagAO commissioning runs.

We were granted two nights of time in 2014A to begin the survey and these nights were a great success. We have also been granted 1.5 nights of time in 2014B to observe the B semester targets in the sample, however these observations have not yet been completed.