OBSERVING REQUEST
University of Arizona Observatories

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

Probing of the habitable zone of α Centauri A with MagAO/Clio2/VisAO (MagAO Key Project)

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Abstract of Scientific Justification

MagAO's Clio2 and VisAO cameras are now capable of searching the habitable zone (HZ) of α Cen A – the nearest sun-like star. We have demonstrated on-sky that we will be sensitive to gas giant extrasolar planets down to at least $0.1M_{Jup}$. We can achieve this sensitivity using MagAO's exceptional performance in two ways. **Thermal:** In the HZ the minimum temperature of an extrasolar giant planet (EGP) will be set by irradiation, and since EGP radius is only weakly dependent on mass (from $\sim 0.1M_{Jup}$ to $10M_{Jup}$ EGPs have a radius of $1R_{Jup}$ to within 20%), the luminosity of an EGP ($\propto R^2T^4$), is likewise only weakly dependent on mass. So once we are sensitive to some minimum brightness, we can detect almost any gas giant in the HZ. With Clio2's M-band imaging capability we will search the inner HZ of α Cen A for low-mass EGPs. These observations will make use of a new highly optimized coronagraph designed and funded specifically for this project. **Visible:** Models of EGPs predict that inside 2 AU from a G star such planets will become very bright in reflected visible light (albedo ~ 0.7) due to water clouds. We have demonstrated, on-sky, visible (i') contrasts approaching 10^{-8} in the outer HZ of α Cen A – sufficient to begin placing limits on the presence of EGPs there. We propose to continue our probe of the HZ of α Cen A using MagAO with Clio2 and VisAO, providing the most sensitive search of a sun-like star's HZ to date. These observations are fundamentally different from the typical search for young self-luminous planets at wide separations. This search is the MagAO Key Project, which involves collaborators from around the Magellan consortium who are also contributing time.

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	Clio2 and VisAO		*	2	bright	May–Jun	May–Jun	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: Based on tentative scheduling of MagAO 2015A installation on Clay

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	α Cen A	14:39:36	-60:50:02	G2V, $R = -0.5$, $M' = -1.5$

Approval for Instrument Use from PI: N/A

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

MagAO is now sensitive to extrasolar giant planets (EGPs) in the habitable zones (HZs) of several nearby bright stars, using a combination of thermal-IR imaging with MagAO+Clio2 and in the visible with MagAO+VisAO.

Thermal-IR: We motivate our program with the following scaling arguments. EGP radius R_P does not depend strongly on mass M_P, i.e. $R_P \propto M_P^{1/10}$ for an H/He gas giant (Fortney et al, 2011). This trend appears to hold to at least $0.1M_{jup}$ (Males et al, 2014). Our second premise is that close to the star (in the HZ and closer) the minimum EGP temperature T_P will tend to be set by irradiation, not mass or age. For the sake of argument, we take this minimum temperature to be roughly the equilibrium temperature for a blackbody, given by $T_{eq} \approx 278.5L_*^{1/4}a^{-1/2}$K where L_* is the star's luminosity in solar units and a is the planet's separation in AU. We are neglecting the albedo and distribution factor for now. Taken together these two points imply that close to a star the minimum luminosity of an EGP, which will be proportional to $R_P^2 T_{eq}^4$, is essentially independent of mass and age. A planet search in this regime is fundamentally different from all direct imaging campaigns to date, which have concentrated on imaging young self-luminous planets at wider separations.

This regime, where $T_P = 200 - 300$K and where irradiation is important, is not widely modeled in the literature. For such relatively cool planets a comprehensive set of models are the well known COND models (Baraffe et al., 2003). We use these evolutionary tracks to find R_P and T_{eff} for a given age and mass, extending the grid to $0.1M_{Jup}$ using the above radius and luminosity scalings. Then, for a grid of separations from the star and assuming a Bond albedo of 0.34, if $T_{eq} > T_{eff}$ we use T_{eq} as the planet temperature, and then interpolate within the grid of spectra and calculate the M' magnitude of the planet. Note that we do not inflate R_P to match the increase in T_P, so these will be conservative estimates. See Males et al (2014) for additional discussion of this analysis. In Figure 1 we show the resulting M' contrast predictions as a function of mass and separation in and close to the HZ ($\sim 0.6''$ to $\sim 1.6''$). Once we reach 10^{-5} contrast at ~ 0.5", we are sensitive to EGPs of almost any mass as predicted by the scaling arguments above.

New Coronagraph: In Figure 1 (right panel) we show the contrast we have achieved so far in our observations of α Cen A. We are currently hindered by the effects of diffraction at close separations. See the on-sky point spread function (PSF) in Figure 2 (right panel). To remedy this, we are procuring a new apodizing phase plate (APP) coronagraph. We have optimized the design of this coronagraph specifically for this program, and it is being funded by the PI's 2014 Lucas Junior Faculty Award. The PSF of the APP is shown at left in Figure 2. The projected APP coronagraphic contrast as a function of separation, and the resulting detection limits of $\sim 0.1M_{jup}$, are shown in Figure 1. These predictions take into account the advanced PSF subtraction algorithms we have tested with actual observations of α Cen A.

Visible: Water clouds are expected to form in the atmospheres of EGPs by 2 AU, but will have evaporated close to the star (Cahoy, 2010). This causes EGPs to be brightest in reflected light at ~ 1.5AU. The reflected light contrast is given by

$$C = 1.818 \times 10^{-9} \left(\frac{R_p}{a}\right)^2 A_g(\lambda)\Phi(\alpha)$$

where R_p is in Earth radii, a in AU, $A_g(\lambda)$ is the geometric albedo (full phase), and $\Phi(\alpha)$ is the phase function. In Figure 3 (lower right panel) we show the contrasts of EGPs along a projected circular orbit at the outer edge of the HZ. One model of the Sun's HZ places the outer edge at 1.77 AU, so we assumed $a = 1.77\sqrt{L_*} = 2.1AU$ and matched the A-B binary's inclination of 80^o. A_g and $\Phi(\alpha)$ are from the model grid of Cahoy et al (2010). An EGP orbiting 2 AU from α Cen A will be have a contrast of $\sim 2 \times 10^{-8}$ at $1.5''$.

In Figure 3 we summarize the performance obtained on this star in 2014A. In short, we have achieved an extremely good 2×10^{-8} contrast at $1.5''$. This is good enough that **we are now searching the HZ of the nearest G star for EGPs in reflected visible light**. As a result of the observations shown here, we have identified several ways to improve on these already extremely good results. These include optimizing our atmospheric dispersion corrector (ADC) control system, and targeted vibration mitigations (see engineering proposal of L. Close).

Though we are very excited by the contrasts achieved, we have not yet achieved any measure of search completeness. A single look is not enough – we are now working in the regime where orbital periods are short enough that repeated observations will be required to achieve search completeness. See Males et al (2013) for a discussion of how orbital motion impacts observations such as these.

The Nearest Sun-Like Star: At only 1.34 pc, α Cen A is the nearest G star to the Sun. As such it has been a target of planet searches using other techniques. The mass regime we are probing with MagAO is especially interesting, given the incompleteness of RV efforts for such low mass planets. Estimates provided by Wittenmyer et al, (2011), indicate that RV surveys are not complete below roughly the mass of Saturn around α Cen A. That means we can detect planets not yet detected by RV. Orbits as wide as 4AU (3”) have been found to be dynamically stable around both α Cen A&B (Wiegert and Holman, 1997). Finally, the discovery of $\sim 1M_{\oplus}$ planet on a 3.2 day orbit around α Cen B shows conclusively that planet formation is possible in this binary system (Dumusque, 2012).

These observations are fundamentally different from typical searches for young, self-luminous planets, which probe wide separations where planets appear to be rare. MagAO can credibly search a handful of nearby stars at close separations, including α Cen A. The results of RV surveys and Kepler make it clear that planets are common around stars at these distances. This project is a precursor to the surveys we will conduct with the GMT, which, due to its increase in sensitivity and resolution, will be able to extend these observations to smaller planets around a wider sample of stars.

References

Baraffe et al, A&A 404:701, 2003
Cahoy et al, ApJ 724:189, 2010
Close et al, SPIE 2012
Dumusque et al, Nature 491:7423, 2012
Fortney et al, Ch 17, “Exoplanets”, 2011
Males et al, ApJ 771:10, 2013
Males et al, SPIE 9148, 2014
Wiegert et al, ApJ 113:1445, 1997
Wittenmyer et al, ApJ 727:102, 2011

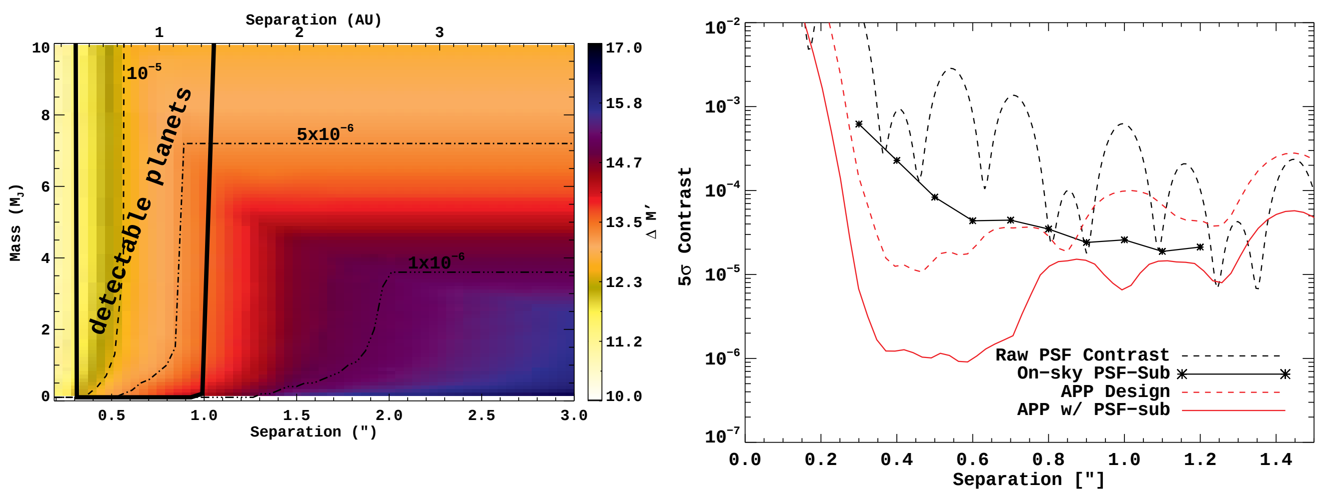

Figure 1: Left: The M’ mass detectability for α Cen A based on the APP prediction in the right panel. Planets within the solid-black curve are detectable by MagAO and Clio2. Right: M’ contrast achieved so far on α Cen A with MagAO (star points). We used the improvement of this over the PSF due to PSF subtraction to predict the ADI-PSF-Subtracted contrast we will achieve with the APP. We will be able to detect irradiated giant planets down to at least 0.1 M_{jup} in and interior to the Habitable Zone of α Cen A. These observations will set the best limits to date on exoplanets around the nearest sun like star.

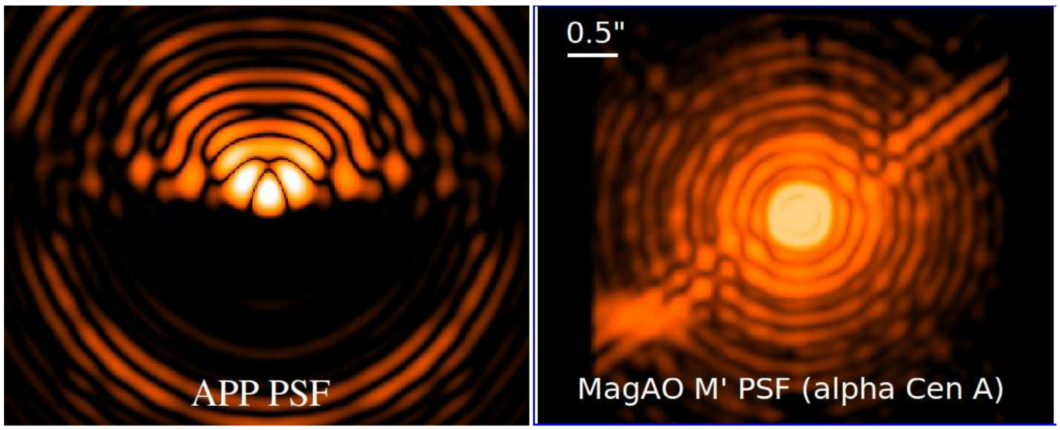

Figure 2: Here we compare the predicted vAPP PSF (left) to that M' PSF obtained on-sky in 2014A, on α Cen A. The dark hole created by the vAPP will allow us to reach 10^{-6} contrast in the habitable zone of the nearest sun-like star.

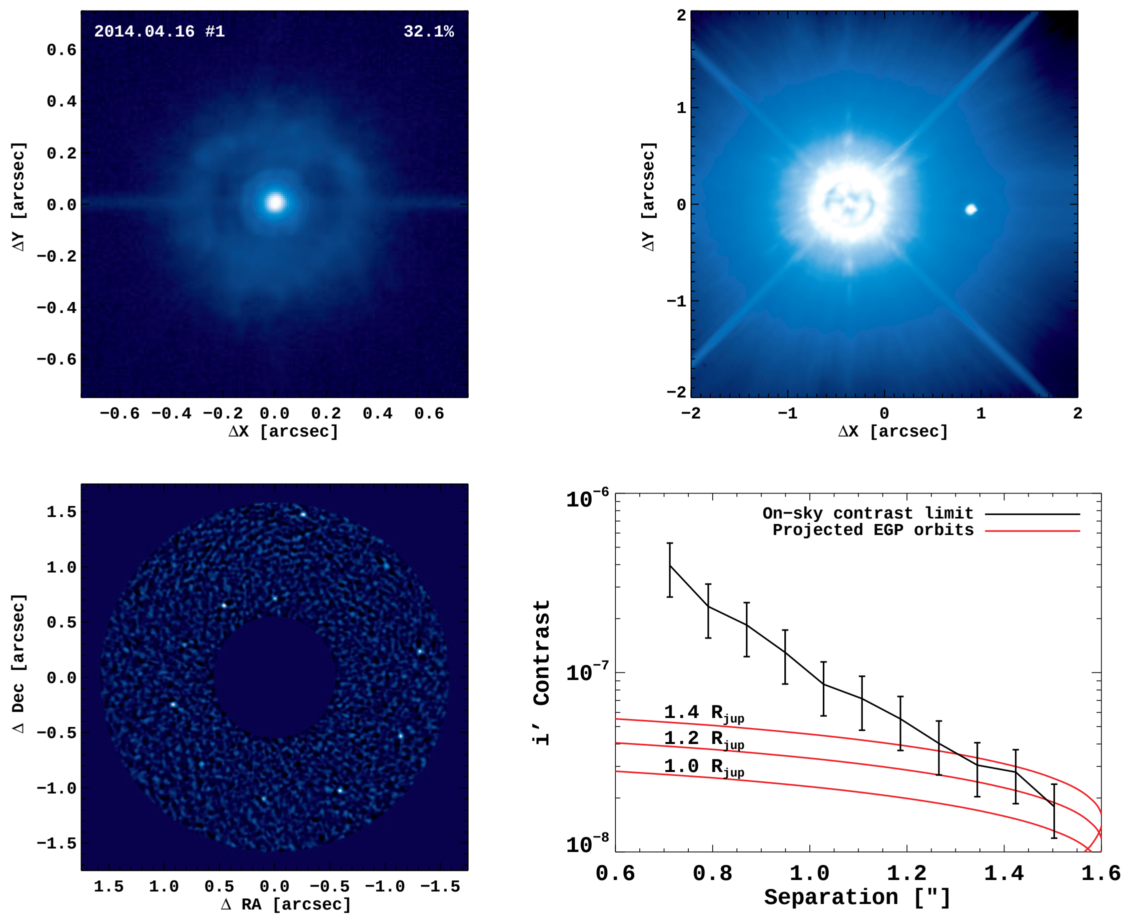

Figure 3: **Top-Left**: an unsaturated PSF in i', 0.77μm, with Strehl ratio of 32.1%. **Top-Right**: the corresponding 4 hour saturated PSF behind the VisAO coronagraph. **Bottom-Left:** a high contrast reduction of 1 nights worth of data. A spiral of fake planets has been injected to calibrate the throughput of the reduction algorithm. **Bottom-Right:** the contrast achieved (combining 3 nights worth of data) compared to the contrasts of putative EGPs orbiting at the outer edge of the HZ. MagAO+VisAO has begun to set limits on the size of EGPs in the HZ of the α Cen A. Additional observations are required to account for the motion of orbiting planets. Note the HZ of α Cen A extends from $\sim 0.6'' to \sim 1.6''$ projected on the sky.

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 proposed observations of α Cen A are part of our MagAO Key Project to perform a reconnaissance of the nearest bright stars at close separations. There has been very little attention paid to the very nearest older stars at close separations. MagAO/Clio2/VisAO provide a powerful and unique multi-wavelength capability to probe this regime for the first time. To fully take advantage of this we have assembled a collaboration from around the Magellan community.

During our observations of α Cen A in 2014A we demonstrated that MagAO can lock on such a bright star, and that both Clio2 and VisAO can be configured to handle the photons. Here we summarize how we set up the cameras and our observing strategies.

Thermal-IR: We will observe α Cen A in M'. We have achieved excellent contrast in this filter (see Figure 1), and there appears to be much better agreement in the models at this wavelength compared to L', and at ~ 5 Gyr old the planets we seek are old and cool enough that the models favor M' over L' due to Methane absorption in L'. For younger planets L' is often a better choice due to better sky subtraction performance, however this star is so bright that we are not sky-limited. So M' is the best choice both observationally and from a science interpretation perspective.

Our observations at M' will be performed using telescope nodding for background subtraction. Data will be taken with the rotator off, to facilitate angular differential imaging (ADI). We will split our time up over several nights, sharing with other observers. This approach is necessary to mitigate speckle noise, by both ensuring that we observe near and through transit to take advantage of high rotation rates, and to help break speckle coherence by stacking data from successive nights.

The new APP design will be installed prior to the 2015A run, and commissioned during engineering time by the MagAO team. It will be employed for these Clio2 observations. The coronagraph creates a dark hole on only 1 side of the star. We will use the telescope rotator to position this dark hole to optimize search completeness.

Visible: With VisAO, we will use the SDSS i' filter where EGPs are predicted to have high albedo (~ 0.6) at ~ 1.5AU (luminosity scaled). We will run the CCD-47 in its highest clock speed (2.5MHz), with a 512x512 window, giving a frame speed of 6.7Hz. We will use the VisAO coronagraph, placing A behind the occulting mask and keeping B off the chip. This setup will allow us to achieve at least 60 degrees of rotation without B landing on the CCD47 (and thus saturating it). This strategy has been effectively employed as shown in Figure 3.

Time Justification: The VisAO on-sky contrast limits, shown in Figure 3 (lower right), were obtained with 3 observations of $4-5$ hrs each. We are $\sim 1.8/1.3$ away from reaching a $1R_{jup}$ planet. In the contrast-limited regime, where we are using ADI to break speckle coherence, contrast will scale with the number of such observations as $C \propto \sqrt{N}$. To push our contrast limit below $1R_{jup}$, we therefore need at least $N \geq 3 \times (1.8/1.3)^2 \sim 6$ such observations. By sharing with other observers, the 2 nights we request here will provide 4 to 5 such observing blocks. When combined with the time contributed by our collaborators, we will push our contrast limit below $1R_{jup}$.

2 nights split into 4-5 observing blocks will also allow us to use multiple orientations of the APP coronagraph in M'. This will be necessary to fully sample all position angles.

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**)*

During the 2013A commissioning 2 run (April 2013) we observed α Cen A for approximately 6 hours total. This time was primarily used to optimize the system for the brightest stars in the sky.

We received 1 night in 2014A for this project, which was spread over 3 nights (~ 4 hrs each) in cooperation with other observers. In addition, 1.5 nights were contributed by collaborators at CfA and Michigan.

This is an Arizona led effort. This research is the primary focus of the PI's NASA Sagan Fellowship. We are asking for 2 nights from Arizona for this project. Our collaborators at Carnegie DTM, Harvard, Michigan, and MIT are combined contributing 1.5 nights total through their respective TACs.

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 received 1 night of UAO time in 2014A. A paper is in preparation to report on the VisAO contrasts shown in Figure 3 (Males et al, in prep).

We conducted engineering tests in support of this project during MagAO's 2013A commissioning period.

We have made excellent use of our MagAO commissioning runs. We demonstrated the high contrast imaging capabilities of VisAO with the first CCD image of an exoplanet (β Pic b):

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

Other MagAO publications include:

Biller, Males, et al., "An Enigmatic Pointlike Feature within the HD 169142 Transitional Disk." ApJ 792:L22, 2014

Close, Follette, Males, et al., "Discovery of Halpha Emission from the Close Companion inside the Gap of Transitional Disk HD 142527." ApJ 781:30, 2014

Follette, K. B., 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., 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., et al. "High Resolution H alpha Images of the Binary Low-mass Proplyd LV 1 with the Magellan AO System". ApJ, 775, 45, 2013

Kopon, D., 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