# OBSERVING REQUEST
## University of Arizona Observatories

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

# Using MagAO to constrain the energy budget and characterize the atmosphere of an exoplanet to be discovered by GPIES


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**CoI(s):** Bruce Macintosh (Stanford), Jenny Patience (ASU), Travis Barman (LPL), Laird Close (SO), Jared Males (SO), Phil Hinz (SO), Rob De Rosa (Berkeley), Pascale Hibon (Gemini South), Christian Marois (NRC-NSI), Abhi Rajan (ASU), Jason Wang (Berkeley), Kim Ward-Duong (ASU), GPIES Team (Various)



**Abstract of Scientific Justification**

Radial velocity and transit photometry (*e.g. Kepler*) surveys have discovered some ~5000 exoplanets to date; however, these extrasolar planets tend to be on <1 AU orbits and quite dissimilar from Solar System planets. Direct imaging, therefore, remains the technique of choice to discover and characterize young Jupiter analogs at >5 AU separations. The technique of direct imaging requires cutting-edge adaptive optics (AO) instruments optimized for high-contrast imaging of faint planets located <1" from bright stars. GPIES is the Gemini Planet Imager Exoplanet Survey, an approved long-term campaign using the GPI instrument in Chile that was approved by Gemini in 2011. With first-light in 2013 and 4 commissioning runs completed in 2014, GPI is now ready for the campaign. In November 2014, GPIES will begin our 890-hour 3-year survey of 600 nearby young stars to look for planets in a unique search space. GPI will characterize the planets with $YJHK$ low-resolution integral-field spectroscopy. However, the 3–5 $\mu$m observational capability of MagAO/Clio2 is critical to fully characterizing the atmosphere and constraining the energy budget. This is because the spectrum peaks in this wavelength range for $500 \lesssim T_{\rm eff} \lesssim 1200$ K, and because the fundamental bands of CO, $CO_2$, and $CH_4$ are in this part of the spectrum. Using Magellan AO to follow-up GPIES-discovered exoplanet(s) will multiply the GPI science value by leveraging the unique niche filled by MagAO. We ask for 0.5 night with MagAO for follow-up in June 2015. We admit to the TAC that we predict to have found only ~1–2 planets by this date, so we also have a back-up plan in place, in case 0 planets are found by June 2015. The back-up plan is to extend by 0.5 night the other MagAO-GPIES proposal, led by Ward-Duong of ASU, for wide-field reconnaissance of GPIES targets.


**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 | MagAO+Clio2/VisAO | * | * | 0.5 | bright | Jun | Jun | yes | yes |

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

*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 | Newly discovered exoplanet(s) | 13–17 hr. | <+25 deg. | Host star: $I$<9, $d$<150 pc, age 10–300 Myr |
| 2 | Will be from this list: http://www.gemini.edu/sciops/instruments/gpi/campaign-science/gpi-campaign-target-list | | | |

**Approval for Instrument Use from PI:** See email

**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 |
|---|---|---|---|---|
| Abhi Rajan | Jenny Patience | | no | no |
| Jason Wang | James Graham | | no | no |
| Kim Ward-Duong | Jenny Patience | | no | no |

**Scientific Justification**

Finding and characterizing extrasolar planets is meaningful, cutting-edge science that informs our past origins as well as our future directions. The Gemini Planet Imager (GPI) instrument at Gemini South, Chile is a special-purpose instrument designed to achieve a higher contrast on bright stars to look for fainter planets at closer orbital separations than has been done before. Four commissioning runs are now completed and the 890-hour GPI Exoplanet Survey (GPIES) campaign begins in November 2014. GPIES was awarded 890 hours (Queue Band 1) over 3 years to survey 600 stars for planetary companions. The survey is scheduling $\sim$20 nights on GPI in 2015A. We would like to reserve 0.5 night on MagAO in June 2015 to follow-up the $\sim$1–2 planets within the RA range 13–17 we predict to have discovered by that time.

## Prediction of GPIES planet detection

McBride et al. (2011) conducted detailed Monte Carlo simulations of the GPI Exoplanet Survey. Extrapolating the radial velocity (RV) planet occurrence rates out to 75 AU (Cumming et al. 2008, Nielsen et al. 2010), we predict that GPIES will discover 25–50 exoplanets around the 600 nearby young stars surveyed. The range in objects detected reflects the different luminosities of young planets depending on whether they formed like stars via gravitational contraction and then are slowly cooling down ("hot-start", Burrows et al. 2000, Ackerman & Marley 2001), or whether they formed like planets in a disk and have already radiated away much of their heat during accretion ("cold-start", Marley et al. 2007). Fig. 1 shows the results of the simulations. The survey is being designed to increase our chances of detecting a planet in the early part of the campaign, also as shown in the Figure. The result is that our estimate of 1–2 planets (within the RA range 13–17) by June 2015 is a conservative lower limit. However, we recognize that there is still a chance no planets would have been found by June 2015, and thus our back-up plan is to extend the Ward-Duong proposal for GPIES wide-field reconnaissance.

## RA range

Here we explain why our target will necessarily fall within the RA range 13–17 hours (first half of the night in June). GPIES has received a campaign-level time allocation from Gemini for the survey. MagAO, however, is not currently on the telescope long enough for such large-scale surveys. Therefore, we will confirm the planet candidate is bound to the host star with GPI before observing it with MagAO. We require $\sim$3 months to lapse before follow up with GPI, in order to allow enough parallax and proper motion to move a background object a few spaxels on the chip. Therefore, the confirmation must be completed by June 2015, leaving March as the last month for first detection of the planet. The only RAs that are visible in June that are also up earlier in the year within the 3 month follow-up time are RAs 13–17 visible in March, and RAs 13–15 visible in February (RAs up in January have all set by June). GPIES will spend $\sim$1 hour per star, and will cover each star once, prioritized by age, distance, and mass. With $\sim$20 GPIES nights in 2015B, assume an even distribution of 3.3 nights per month. Then within the RA range 13–23, 12 stars can be observed in February and 18 stars in March. This means we have 30 stars around which to find a planet by June 2015. Given the estimated detection rate of 4–8% (McBride et al. 2011), we would simplistically assume that around any 30 stars in the GPIES catalog, we would find 1–2 planets. However, this is a conservative lower limit, as we expect the detection rate to be higher, early in the campaign (see Fig. 1). Therefore, while there is some risk to this proposal, we feel that the time is right because there is a very high chance we will indeed have a planet to follow-up by June 2015.

## Importance of MagAO/Clio2

GPI covers 1–2.5 $\mu$m in 5 filters ($Y$,$J$,$H$,$K1$,$K2$) with an Integral-Field Spectrograph (IFS) with low resolution spectra of R$\sim$50. This is sufficient to measure gravity at $H$-band and deep absorption features. However, the addition of 3–5 $\mu$m light with MagAO/Clio2 adds two crucial pieces of information: (1) the effective temperature can be found with fewer degeneracies in the thermal infrared where the energy is being emitted the most strongly, and (2) the molecular features can be determined more easily at these wavelengths where the fundamental bandheads are (whereas the overtones are at 1–2.5 $\mu$m and thus not as prominent).

Extrasolar giant planets (EGPs) on wider orbits emit the bulk of their energy at 3–5 $\mu$m (see Fig. 2), and so it is crucial to observe these planets in the $L'$ and $M'$ bands, to determine their bolometric luminosities on which so many other properties rest. Bolometric luminosity and age are used to infer the mass of a directly-imaged planet for an adopted evolutionary model set. Therefore, large errors in $L_{bol}$ lead directly to large errors in inferred mass. We plan to mitigate this by obtaining photometry at thermal-IR wavelengths of planets detected in the near-IR with GPI.

MagAO/Clio2 is the only US facility poised to give complete SED coverage of GPIES-detected planets including thermal emission. Therefore, we believe it is in Arizona's best interests to award 0.5 night for this program, to allow an Arizona team to follow-up the GPIES planet(s) before publication.

## An example of MagAO + GPI synergy: $\beta$ Pic

$\beta$ Pictoris is a $\sim$23-Myr-old A-star 19.44 pc away that hosts a $\sim$1000-AU disk of gas and dust, and a giant planet embedded in the disk at $\sim$9 AU separation. We observed this system with MagAO+VisAO/Clio2 in 2012 Dec. in 5 bands from 0.93–5 $\mu$m. Fig. 3 shows the results. This example shows what we would like to do with the GPIES follow-up.

## Team

Investigators who are GPIES members include the Arizonans Morzinski, Patience, Ward-Duong, Rajan, and Barman; Macintosh (the PI of GPI and GPIES); and other non-Arizona-affiliates. Because we are carrying out this program in coordination between the GPIES and MagAO teams, we will have direct early-access to the GPI-discovered planets ($\Delta$H, separation, and position angle) before they are made public — hence we have a unique path for multiplying the GPI science value to the exoplanet community.

## References


Ackerman, A. S. & Marley, M. S., 2001 ApJ, 556, 872.
Burrows et al. 2000, ApJ 531, 438.
Cumming et al. 2008, PASP 120, 531.
Fortney, J. et al. 2008, ApJ 683, 1104.
Males, J. et al. 2014, ApJ 786, 32.
Marley, M. et al. 2007, ApJ 655, 541.
McBride, J. et al. 2011, PASP 123, 692.
Morzinski, K. et al. 2014, in prep.
Nielsen, E. et al. 2010, EASPS 41, 107.
Skemer, A., et al. 2014, ApJ 792, 17.
Sorahana, S. & Yamamura 2013, PPVI.


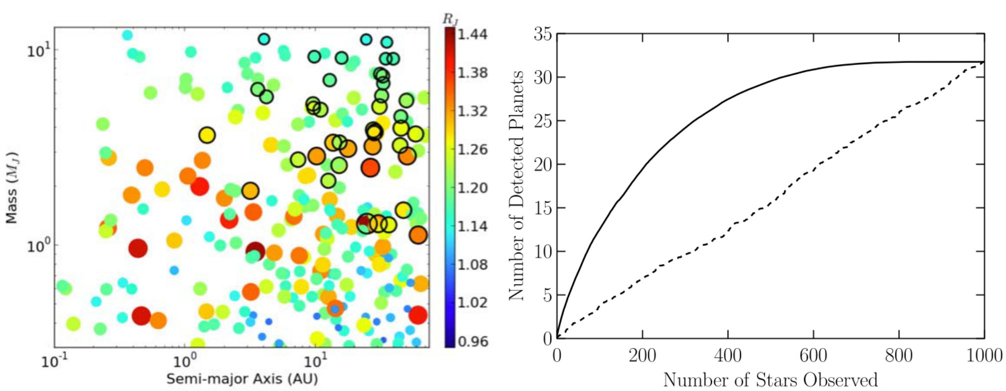


**Figure 1** Predictions of planet discoveries (McBride et al. 2011). Left: Sample population of Cold-start planets (circled planets detected). Because of the less challenging contrast requirements at 3–5 $\mu$m as compared to 1–2 $\mu$m (see Fig. 2), most of these planets will also be detectable with MagAO. Right: The expected number of detected planets, shown for two observing strategies (McBride et al. 2011). The dashed black line indicates targets chosen randomly from a sample of stars younger than 1 Gyr and within 70 pc. The solid black line shows the results when the targets are scored by the age, distance, and mass of the star. This prioritizes the lower-hanging fruit so that our prediction of 1–2 planets is actually a conservative lower limit on the number of planets detected within the early months of the survey.

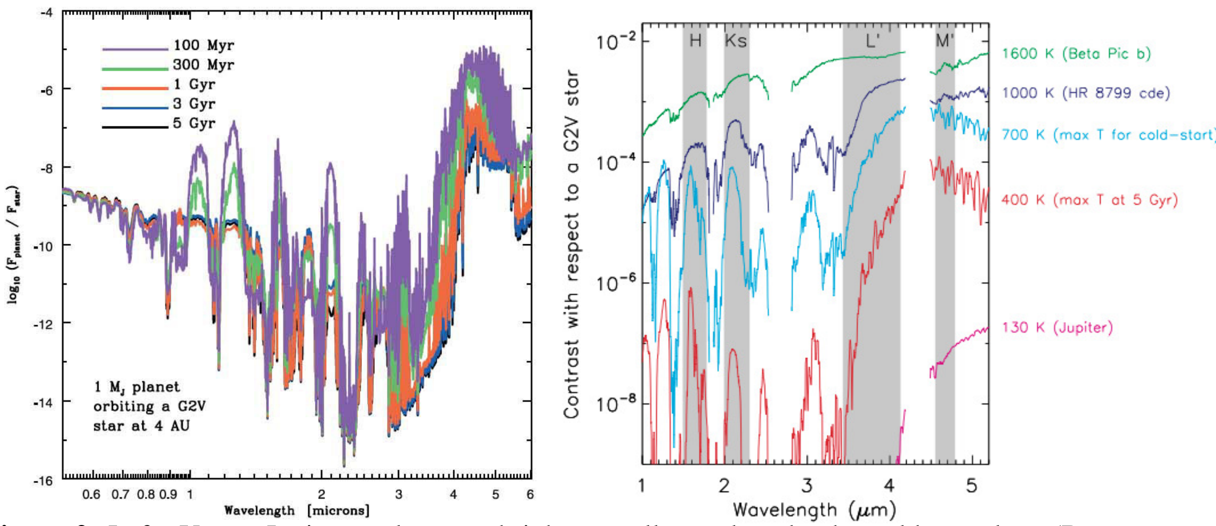


**Figure 2** Left: Young Jupiter analogs are brighter at all wavelengths than older analogs (Burrows et al. 2004). At all ages, the bulk of the energy is emitted around $\sim$4 $\mu$m, so MagAO/Clio2 observations are needed to contribute an important part of the picture. Right: Contrast requirements are less challenging for longer wavelengths (Skemer et al. 2014), which is why MagAO will be able to successfully detect the GPIES-discovered planets. See Tab. 1 in the next section for a comparison.

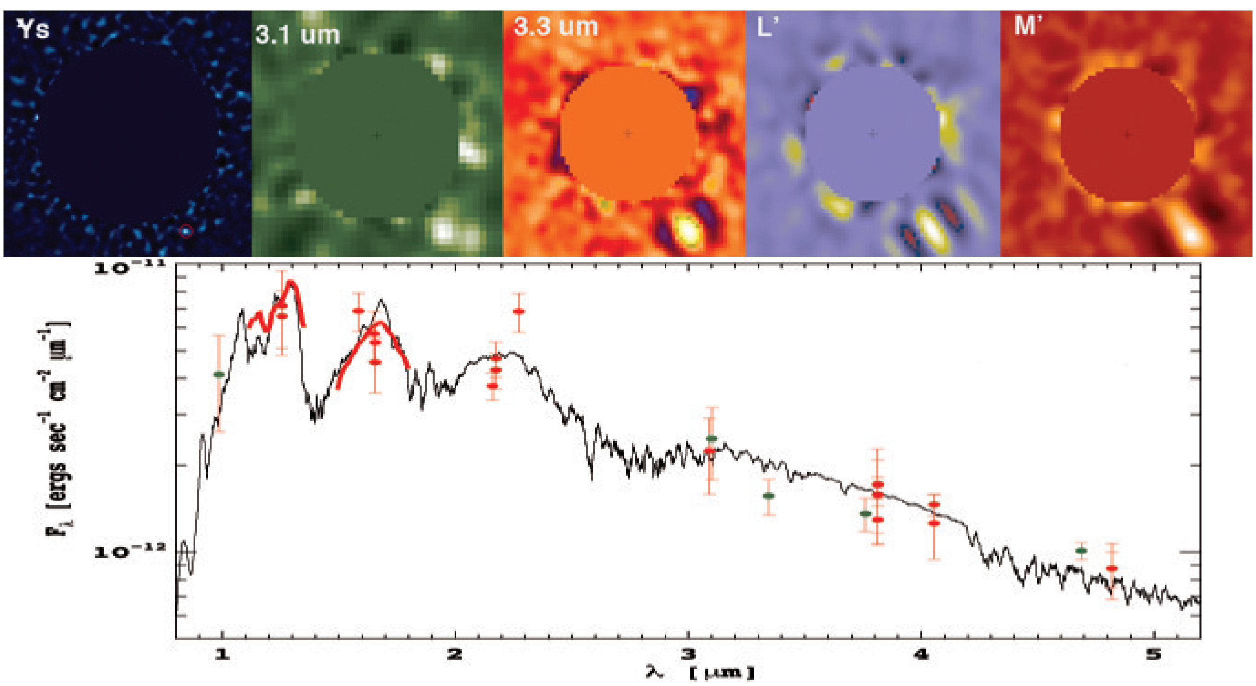


**Figure 3** Top: Residual images of $\beta$ Pic b (linear scale) after using principal-component analysis (PCA) to determine and subtract the PSF. Left to right: VisAO: $Y_s$ (Males et al. 2014); Clio2: 3.1 $\mu$m, 3.3 $\mu$m, $L'$, and $M'$ (Morzinski et al. 2014). Each image is 0$''$.5 across. Bottom: $\beta$ Pic b spectrum. Green points are from MagAO+VisAO/Clio2; Red points are from VLT/NaCo and Gemini/NICI; Red $J$ and $H$-band spectra are from GPI. A best-fit BT Settl model is plotted. The [3.3] point from MagAO/Clio2 falls below the model and is suggestive of $CH_4$ absorption, as seen in L-dwarfs as early as L5 by the *AKARI* satellite (Sorahana & Yamamura 2013). $\beta$ Pic b's low gravity may allow thick clouds that mute some of the $CH_4$ signature in the overtone at $H$ band while allowing it to be seen in its fundamental absorption band at 3.3 $\mu$m. MagAO/Clio2 photometry error bars are smaller than VLT/NaCo and Gemini/NICI due to the extremely good AO performance allowing the best PCA-based PSF subtraction.

**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)***

If there is one planet then we will spend our 0.5 night on it alone; if there are two planets then we will divide the time. We will focus on getting a significant photometric signal at the most significant passbands, [3.3] and $L'$. We will use a new vector Apodizing Phase Plate (APP) coronagraph that is being procured by Males, Morzinski, and Close. This vAPP should provide a contrast of $\Delta L' \sim 10$ sufficient to detect a $T_{eff} \sim 700$-K planet at $0\farcs2$ (the inner working angle of both GPI and MagAO), and $\Delta L' \sim 12.5$ sufficient to detect a $T_{eff} \sim 400$-K planet at $0\farcs5$ (see Fig. 2).

**Table 1** Contrasts required to image various planets with respect to a G2V star, also shown in Fig. 2, calculations by Skemer et al. 2014.

| $T_{eff}$ | Contrast at $H$ | Contrast at $L'$ |
|---|---|---|
| 1600 | 7.5 | 5.3 |
| 1000 | 9.3 | 7.5 |
| 700 | 11.3 | 10.0 |
| 400 | 17.5 | 12.5 |

Because we will know the locations of the planets ahead of time, using an APP with a half-dark hole is fully efficient, as we will rotate the instrument to position the planet in the dark hole. Using these advanced high-contrast observing techniques, our images will be sensitive at $0\farcs2$ around solar-type stars to core-accretion planets (Fortney et al. 2008) of 1 $M_{\rm Jup}$ at 1 Myr, or a few $M_{\rm Jup}$ at 10 Myr; or to hot start planets (Fortney et al. 2008) extending to even lower masses and older ages.

We will also attempt a detection with VisAO, most likely in H$\alpha$ if the star is particularly young, but we admit this is a very challenging observation and would require some serendipity in terms of an accretion event or other reason why the faint planet would be detectable with VisAO. However, the observations come for "free" for guide stars brighter than $R \sim 10$, and because GPI has a magnitude requirement of $I < 9$, the target will certainly be bright enough to take VisAO data. (For fainter stars, we have to send a greater fraction of the visible-light photons to the wavefront sensor, making VisAO no longer "free" but coming at a cost to AO performance. Luckily this will not be the case.) Males, the VisAO instrument scientist, has already succeeded in imaging $\beta$ Pic b at $0\farcs4$ at a contrast of $\Delta Y_s$=11.97, so there is certainly a chance we will be able to see the planet with VisAO too.

We are experienced in reducing and analyizing high-contrast imaging data. We will use Principle Component Analysis (PCA) as is now standard in this field to determine the best PSF to subtract.

This is not submitted as a ToO because this is not a temporally-occuring phenomenon; rather, the target is T.B.D. but the phenomenon being characterized is the bulk, global properties of the newly discovered planet(s).

**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**)*

**P.I.** Morzinski is a Sagan Fellow at Steward from Nov. 2011–Oct. 2014 and her fellowship was awarded specifically for this work: integrating and commissioning the high-contrast MagAO instrument and then using it to constrain EGP atmospheres at 0.5–5$\mu$m, as follow-up to Gemini Planet Imager (GPI) detections. Beginning Nov. 2014 she is the MagAO Instrument Scientist at Steward.

**Team** Each member of the team is interested and experienced in exoplanets and instrumentation. Core members of the MagAO/VisAO/Clio2 instrument team are listed because their work is critical to obtaining these observations. Professor Patience is a lead Co-I of the GPI science team and also interested in characterizing young exoplanet atmospheres, and brings with her a team of students and postdocs whose help will be critical to managing the data and analysis. Professor TB is also a lead Co-I of the GPI science team and is an expert in modeling substellar atmospheres.

We would like to see the community of Arizona astronomers capitalize upon our telescope resources to secure a leadership position in the observational aspects of the emerging field of comparative exoplanetology.

**Scope** This is a pilot, in that we hope in future semesters to have many more objects to observe!

**Other facilities** No other US facilities are suitable for this project. Also, we are not submitting this proposal to any other Magellan TACs, in this first pilot round.

**Time** We request 0.5 night for this program in 2015A. The target(s) will be imaged in Clio2 bandpasses ([3.1], [3.3], $L'$, $M'$) with a characteristic integration time of 2 hours per target per filter, up to 4 filters, up to $\sim$0.5 night.

**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)***

Over the past 2 years, Morzinski has not applied for any time for the present project. Morzinski had 4 nights of MMTAO time in Jan. 2012 to follow-up brown dwarf candidates in the Hyades, resulting in the following publication:

Morzinski et al. (2012) Proc. SPIE, "High-contrast imaging in the Hyades with snapshot LOCI" and two publications in prep.

PI Morzinski is a core member of the MagAO team, and she was responsible for scheduling the queue, taking Clio2 data, and commissioning the Clio2 camera during both commissioning runs of 2012–2013, each time spending a month with the instrument at LCO.

Morzinski's science work related to this project from commissioning is nearing submission:

⋆ Morzinski et al., "Magellan Adaptive Optics first light observations of $\beta$ Pic b. II. High-contrast imaging at 2–5$\mu$m with MagAO/Clio2", ApJ in prep, 2014.

(Preliminary results were presented orally at 3 recent meetings, including 2 conference proceedings: AO4ELT in Florence in May, and IAU 299 in Victoria in June).

⋆ De Rosa et al. 2014, The VAST Survey - IV. A wide brown dwarf companion to the A3V star $\zeta$ Delphini, MNRAS, accepted

⋆ Males et al., "Magellan Adaptive Optics first light observations of $\beta$ Pic b. I. Direct imaging in the far-red optical with MagAO/VisAO and in the near-IR with NICI", ApJ 786, 32, 2014.

⋆ Skemer et al., "First light LBT AO images of HR 8799 bcde at 1.65 and 3.3 microns: New discrepancies between young planets and old brown dwarfs", ApJ 753, 14, 2012.

⋆ Skemer et al., "Directly imaged L-T transition exoplanets in the mid-infrared", ApJ 792, 17, 2014.

⋆ Ward-Duong et al. 2014, IAUS, 299, 74

Other results from commissioning MagAO include, which are crucial pathfinders for our more challenging observations:

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.

Close, L. M., et al., "Discovery of H$\alpha$ emission from the close companion inside the gap of transitional disk HD 142527", ApJL, 781, 2, L30, 5, 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.

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.