1.0 Overview and Science Justification

Jared Males, Laird Close and the MagAO-X Team

1 Introduction

AO systems are now in routine use at many telescopes in the world; however, nearly all work only in the infrared (IR, $\lambda > 1$ μm) due to the challenges of working at shorter wavelengths. The Magellan AO (MagAO) system was the first to routinely produce visible-AO science on a large aperture telescope. In Figure 1, we show an example of the power of large diameter visible-AO. Other large telescopes with visible AO systems include the 5 m at Palomar (Dekany et al., 2013) and ESO's 8 m VLT with the ZIMPOL camera behind the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) (Roelfsema et al., 2014).

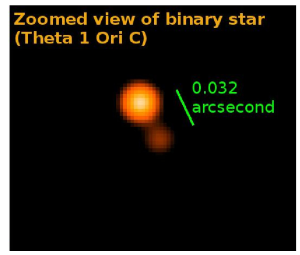

Figure 1: MagAO/VisAO r' image of the 32 mas binary θ^1 Ori C (Close et al., 2013).

1.1 Introduction to MagAO-X: MagAO-X is a *new* visible-to-near-IR "extreme" AO (ExAO) system which is now preparing for its first shipment to Las Campanas Observatory. MagAO-X is an ExAO system optimized for working in the optical ($\lambda < 1$ μm) while (eventually) providing imaging and spectroscopic capabilities out to H band (1.6 μm).

MagAO-X currently consists of: a 2040 actuator MEMS deformable mirror (DM) controlled at (up to) 3.6 kHz by a pyramid wavefront sensor (PyWFS); A 97 actuator ALPAO DM serving as a woofer; a 2nd 97 actuator ALPAO DM serving as a non-common path aberration corrector (NCPC); cutting-edge vector apodizing phase plate (vAPP) coronagraphs to block a star's light; a low-order WFS channel which controls the NCPC DM; and a pair of EMCCD science detectors which enable high-contrast and high-resolution science.

MagAO-X will deliver high Strehls ($\gtrsim 70\%$ at Hα), high resolutions ($14-30$ mas), and high contrasts ($\lesssim 10^{-4}$) from $\sim$ 1 to 10 λ/D . Among many compelling science cases, MagAO-X will revolutionize our understanding of the earliest stages of planet formation, enable high spectral-resolution imaging of stellar surfaces, and could take the first images of an exoplanet in reflected light.

MagAO-X is designed to be shipped to and from the Clay Telescope at LCO repeatedly. This enables a phased commissioning plan, allowing us to manage the complexity and risk more effectively than possible if a finished instrument were delivered at once. It also more efficiently uses telescope allocations during commissioning, as it provides time to analyze critical on-sky results and re-optimize the instrument between runs.

2 Science Justification

For the purposes of this review, we are focusing on one main science case: a survey of nearby T Tauri and Herbig Ae/Be stars for newly formed accreting planets in Hα. We describe this science case in the following section and present the high level performance requirements we derive from it.

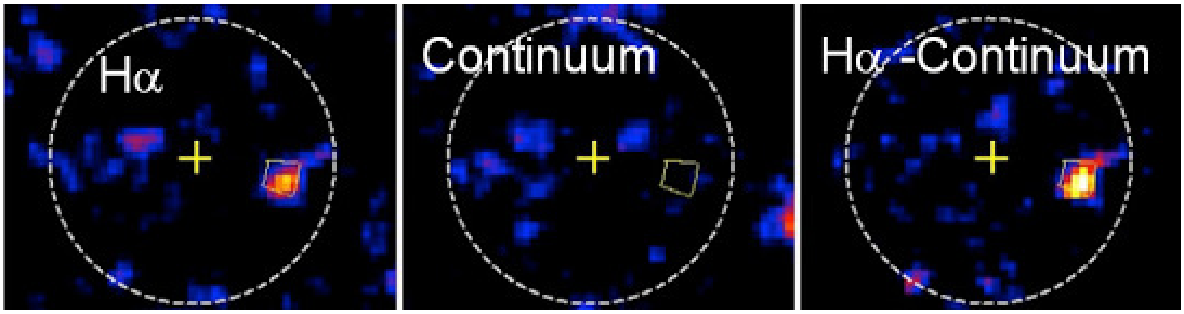

Figure 2: LkCa 15 b, a protoplanet imaged with SDI at $H\alpha$. Sallum et al. 2015.

2.1 A Survey of the Low Mass Distribution of Young Gas Giant Planets: We now know that wide (>30 AU) massive (>4 M_{Jup}) giant planets (EGPs) are rare (e.g. Biller et al., 2013). Yet there are hints of a major population of lower mass (0.5–$2M_{Jup}$) EGPs closer in, from ∼5–20 AU (Sallum et al., 2015). Such EGPs may well determine the delivery of volatiles to potentially habitable inner terrestrial planets (Raymond et al., 2004; Matsumura et al., 2015). A key goal of the decadal Astro2010 survey is the *characterization of habitable planets*, as well as understanding planet formation. MagAO-X will image protoplanets in $H\alpha$ (for H recombination $H\alpha$ is ∼1760% stronger than the best near-IR line Paβ) in the luminous accretion phase of formation to address these goals (not possible with GPI's IR IFS).

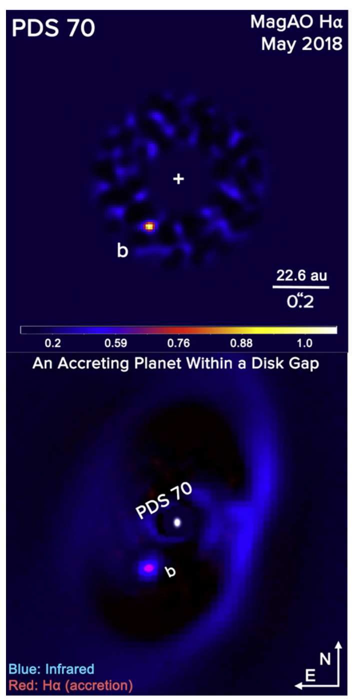

Figure 3: PDS 70 b, a protoplanet imaged with SDI at $H\alpha$. Wagner et al.

2.1.1 MagAO-X $H\alpha$ Protoplanet Survey (MaXProtoPlanetS): While LkCa 15 (145 pc; 1–2 Myr) is fairly faint (I~11 mag) there are many brighter, closer similarly young accreting targets. In the η Cha (Mamajek et al., 1999), ϵ Cha (Murphy et al., 2013), ρ Oph (Luhman & Rieke, 1999), TW Hya (Mamajek, 2005), and Upper Sco (de Zeeuw et al., 1999) clusters, which are all <5-10 Myr old within $\lesssim$150 pc, there are ***exactly 160 individually vetted accreting targets with I≤10 mag.*** These are good guide stars for Phase I of MagAO-X. Around all these target stars a planet like LkCa 15 b would be at ~100–200 mas separations (~15 AU), but instead of $\Delta H\alpha$=5.3 mag it could (conservatively) be 5 mag fainter still — due to extra dust extinction (no disk gaps like LkCa 15), and/or lower mass of the planet. The worst case $\Delta H\alpha$~11 mag contrast is too high for the *existing* MagAO but will be achievable with MagAO-X. Utilizing MagAO-X's SDI+vAPP mode, we will observe the H_α/H_β line ratio that can be compared to Case-B recombination theory (Hummer & Storey, 1987); hence, the line of sight extinction (A_R) can be estimated (Close et al., 1997). As a result, the true $H\alpha$ line strength can be measured and protoplanet masses estimated (Close et al., 2014), see Fig. 4. An I=10 mag star in median conditions with a 0.5 M_{Jup} EGP and 2.5 mag greater A_R and the same $\dot{M}$ as LkCa 15b ($\Delta H\alpha$ =10.3 mag) will have peak pixel S/N~11 in 2 hrs with our KLIP (Soummer et al., 2012) pipeline (accounting for EMCCD excess noise, MagAO-X+vAPP throughput, Strehl and contrast).

There are six (2 of spectral type A and 4K spectral types) I<10 mag targets in the η Cha cluster (50 pc, ~10 Myr) (Mamajek et al., 1999), 15 I<10 targets (1B, 4A, 2G, and 8K SpT) in the ϵ Cha cluster (100 pc, $3--5$Myr) (Murphy et al., 2013), two I<10 targets (1B and 1A SpT) in the ρ Ohp cluster (140 pc, 1 Myr) (Luhman & Rieke, 1999), 17 I<10 targets (2A, 3K, and 12M SpT) in the TW Hya cluster (50 pc, ~10 Myr) (Mamajek, 2005), and finally an additional 120 I<10 targets (49B, 34A, 22F, 9G, 4K, and 2M SpT) in the Upper Sco cluster (150 pc, 5–10 Myr) (de Zeeuw et al., 1999). **So there are a total of 160 <10 Myr old accreting D<150 pc targets all with I<10 mag for the MaXProtoPlanets survey—all bright enough for good AO correction.** There are also many slightly fainter targets I<12 mag that will be dis.

Extrapolating from our initial ($3/10 = 30\%$) success rate for the young star GAPplanetS $H\alpha$ survey having accreting objects (Follette et al., 2016) the 160 stars yield ~48 new protoplanet systems using just 5 nights per semester.

In Phase II we can can achieve the same contrasts on fainter I=12 stars which yields 33 more (ϵ Cha, ρ Oph) targets, yielding ~11 more detections —raising the total to ~59 systems. ***MaXProtoPlanetS's ~59× larger sample of detected protoplanet systems will define the population of low-mass outer EGPs, and will help reveal where/how gas planets actually form and grow.*** Integrating over the secure members of the above youngest clusters (ϵ Cha, ρ Oph) yields exactly 16 and 17 (respectively) more 1–3 Myr targets from $10 < I < 12$ mag. These 32 targets should yield another ~11 discoveries, rasiing the total to ~60. ***This would increase the number of known protoplanets systems by ~ 60×, define the population of low-mass outer EGPs, and for the very first time reveal where gas planets actually form.***

2.1.2 High Level Performance Requirements: From the MaXProtoPlanets survey we derive the high level performance requirements for MagAO-X. These are present in Table 1. The main requirement is to achieve the contrast at the given separation. This places requirements on WFC at specific spatial frequencies. Strehl ratio, which is a global image quality metric, is a "soft" requirement – we need high image quality but do not need to achieve an exact Strehl ratio so long as the contrast is achieved.

We note that these requirements are to be met at the end of the NSF MRI funded project, i.e. after several more commissioning runs and laboratory optimization periods.

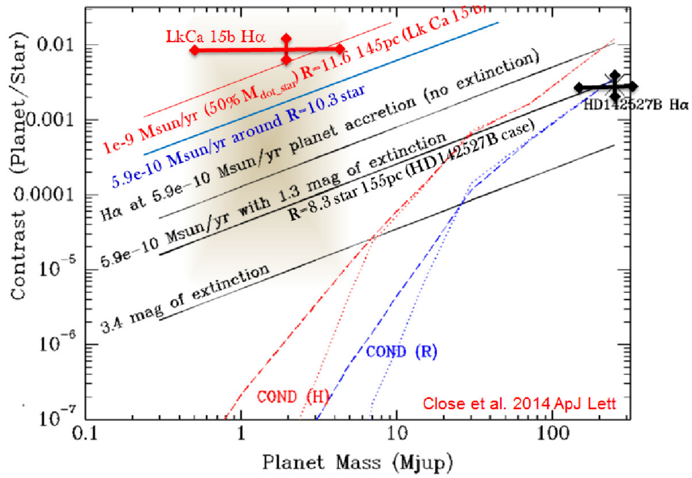

Figure 4: Relation between the mass of the $H\alpha$ planet to the observed contrast (as a function of M_{Rstar}, A_R, & $\dot{M}$ of the planet).

Table 1: The high level performance requirements derived from the MaXProtoPlanets Hα SDI survey.

Targets			Performance		
I mag	d [pc]	Numb.	Sep [mas]	ΔHα mag	Strehl[1] [%]
5	225	6	75	12.0	70
8	150	25	100	9.0	50
10	150	129	100	7.0	30
12	150	44[2]	100	5.0	20

[1] At Hα, λ =656 nm.

[2] not complete, there are likely more

3 Other Science Cases

Here we present a short summary of several additional science cases. These are generally spanned by the parameters of the Hα survey in terms of guide star brightness and separations, and are less-demanding, and so we do not specifically derive requirements for these. Rather, they are presented to give an idea of the breadth of use-cases for this new instrument.

3.1 Circumstellar Disks: Disk science is a challenging application of AO, with low surface brightness and characteristics similar to the uncorrected seeing halo, so high-Strehl high-contrast ExAO is critical. MagAO-X will push the two frontiers in circumstellar disk science. The first is detailed imaging of geometry, particularly in the 5-50 AU region analogous to the outer part of the solar system. Most disks sit at 50-150 pc, so reaching radii comparable to the giant planet region requires imaging at 50-120 mas. Existing systems push in to at best ∼150 mas. For some disks, an inner working angle of ∼100 mas will push to the exozodiacal light region for the first time. For example, in the well-known HR 4796A disk, SED fits show that the 8-20 μm flux cannot be fully explained by the outer, ∼100 K, ring, suggesting a ring at 3-7 AU (Wahhaj et al., 2005). MagAO-X has the

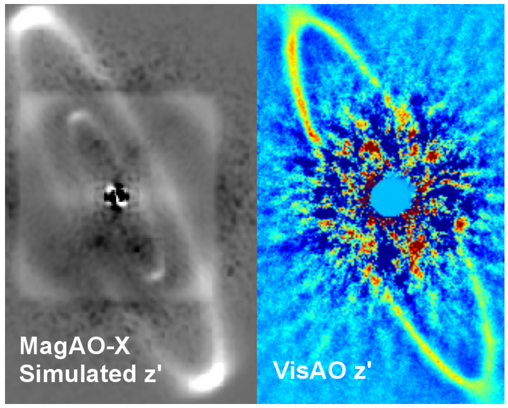

Figure 5: The HR 4796A disk. Left: simulated MagAO-X image at z' (0.9 μm) (includes hypothetical inner disk suggested by Rodigas et al. (2015)), just 5 seconds of data with simple PSF subtraction. Right: actual MagAO+VisAO image (Rodigas et al., 2015). MagAO-X will *significantly enhance our ability to probe the regions closest to the star.*

potential to image this inner ring. The second frontier is multiwavelength study of disks to derive the chemical make-up and dynamical state (Rodigas et al., 2015; Stark et al., 2014). This requires a large wavelength grasp from visible through near-infrared so MagAO-X's ability to image at ∼0.45 μm complements existing systems.

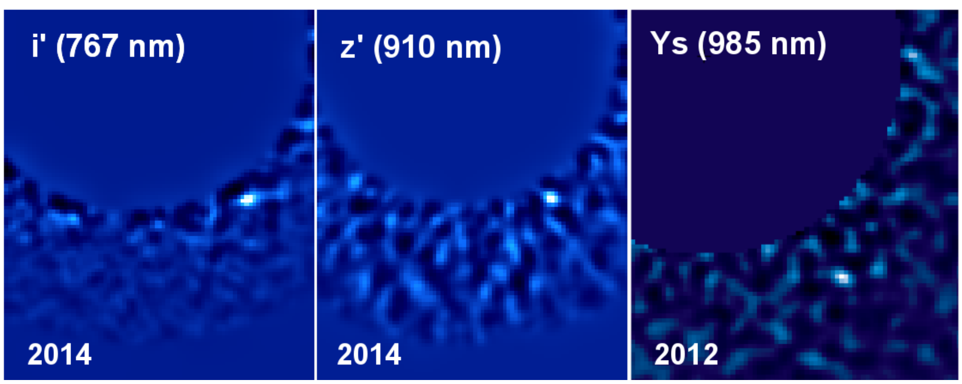

Figure 6: The exoplanet β Pic b imaged with VisAO, in i' & z' (Males et al, in prep) and Ys (separation 470 mas, ΔY_S=11.97 mag, Males et al., 2014). MagAO-X will extend these observations to shorter wavelengths, and fainter, smaller-separation planets such as 51 Eri b.

3.2 Fundamental Properties of Young Solar-System-like EGPs: Dedicated exoplanet-imagers GPI and SPHERE are now operational, and GPI has discovered the first planet of this new era: 51 Eri b is a 600-K ∼2 M_{Jup} exoplanet imaged 13 AU from its 20-Myr-old, 30-pc-away F-type host star (Macintosh et al., 2015). This planet is different from other exoplanets (whether imaged or analyzed by transit spectroscopy): its atmosphere is the closest analog yet to solar system atmospheres because of its Saturn-scale orbit, Jupiter-scale mass, and cool temperature such that CH_4 was detected in the GPI spectrum.

We have conducted a prototype experiment with existing MagAO using the exoplanet β Pic b, which can be imaged with the current VisAO due to its brightness (youth and mass) and its 300-400 mas separation. Fig. 6 shows images of β Pic b taken with the MagAO+VisAO camera (Males et al., 2014). Fig. 7 demonstrates using such measurements to empirically measure the fundamental properties of this solar-system-scale exoplanet—the luminosity of β Pic b (Morzinski et al., 2015). ***MagAO-X will extend these observations to shorter wavelengths, and to smaller mass, smaller separation planets such as 51 Eri b.*** MagAO-X will also enable characterization of such planets with the DARKNESS and RHEA@MagAO-X spectrographs.

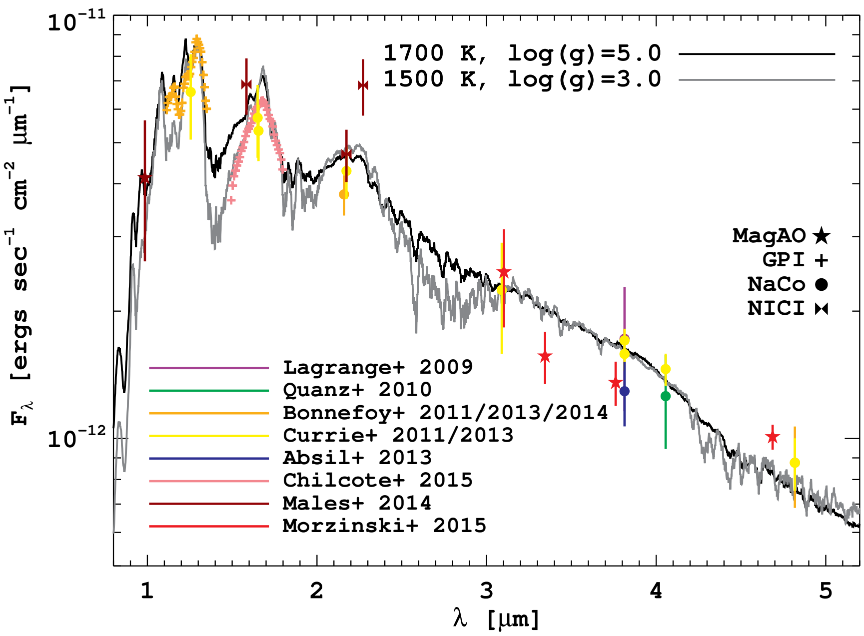

Figure 7: SED of young super-Jupiter β Pic b, with which we measured its bolometric luminosity, empirically for the first time (Morzinski et al., 2015). Plotted black and gray lines are degenerate BT Settl models with identical fits but different temperatures and gravities. MagAO-X will measure the Wien's slope in the visible to give the temperature for this and other young EGPs.

3.3 Resolved Stellar Photospheres: The 3x3 single-mode fiber-fed IFS, RHEA@MagAO-X, with $R \sim$60,000 spectral resolution, will be provided by collaborator Mike Ireland. The combination of the ExAO resolution and contrast with high spectral resolution enables many exciting science cases. For instance: the largest resolvable non-Mira stars accessible from MagAO include Betelgeuse ($\sim$50 mas), Antares ($\sim$40 mas), Arcturus ($\sim$21 mas), Aldebaran ($\sim$20 mas) and α Boo ($\sim$19 mas). These stars lose mass through a complex process in an interplay between a hot ($\sim$10,000 K) corona and a cool ($\sim$2000 K), slow ($\sim$10 km/s) molecular wind. These states can not co-exist so asymmetries of some kind are expected. Resolving the photosphere in lines and molecular bands enables the multi-dimensional structure of these regions to be imaged. Upwelling and downwelling velocities on the surface are of order a few km/s, separable at sufficient resolution. A single image of a stellar photosphere would be the ***first ever direct measurement of convection in a star other than the Sun***.

3.4 Asteroids: MagAO-X will have resolutions of 14–21 mas in g-r bands, which correspond to $\sim$20–30 km on a main-belt asteroid (MBA). On a typical night more than 80 MBAs brighter than I=13 (implying $\gtrsim$ 50 mas) will be resolvable by MagAO-X. This will provide true dimensions, avoiding degeneracies in light-curve analysis. MagAO-X will enable sensitive searches for and orbit determination of MBA satellites. In combination, these directly measure density and hence estimate composition (Britt et al., 2002). This will directly inform the theories of terrestrial planet formation (Mordasini et al., 2011).

4 Pre-Ship Review

The MagAO-X team has produced a set of documents to satisfy the Director's Pre-Ship Review, as well as to provide the review committee with an overview of instrument status and capabilities.

References

Biller, B. A., Liu, M. C., Wahhaj, Z., et al. 2013, ApJ, 777, 160

Britt, D. T., Yeomans, D., Housen, K., & Consolmagno, G. 2002, Asteroids III, 485

Close, L. M., Roddier, F., Hora, J. L., et al. 1997, ApJ, 489, 210

Close, L. M., Males, J. R., Morzinski, K., et al. 2013, ApJ, 774, 94

Close, L. M., Follette, K. B., Males, J. R., et al. 2014, ApJL, 781, L30

de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, AJ, 117, 354

Dekany, R., Roberts, J., Burruss, R., et al. 2013, ApJ, 776, 130

Follette, K. B., Miller Close, L., Males, J., et al. 2016, in American Astronomical Society Meeting Abstracts, Vol. 227, American Astronomical Society Meeting Abstracts, #106.05

Hummer, D. G., & Storey, P. J. 1987, MNRAS, 224, 801

Luhman, K. L., & Rieke, G. H. 1999, ApJ, 525, 440

Macintosh, B., Graham, J. R., Barman, T., et al. 2015, Science, 350, 64

Males, J. R., Close, L. M., Morzinski, K. M., et al. 2014, ApJ, 786, 32

Mamajek, E. E. 2005, ApJ, 634, 1385

Mamajek, E. E., Lawson, W. A., & Feigelson, E. D. 1999, ApJL, 516, L77

Matsumura, S., Brasser, R., & Ida, S. 2015, ArXiv e-prints, 1512.08182

Mordasini, C., Alibert, Y., Klahr, H., & Benz, W. 2011, in European Physical Journal Web of Conferences, Vol. 11, European Physical Journal Web of Conferences, 04001

Morzinski, K. M., Males, J. R., Skemer, A. J., et al. 2015, ApJ, 815, 108

Murphy, S. J., Lawson, W. A., & Bessell, M. S. 2013, MNRAS, 435, 1325

Raymond, S. N., Quinn, T., & Lunine, J. I. 2004, Icarus, 168, 1

Rodigas, T. J., Stark, C. C., Weinberger, A., et al. 2015, ApJ, 798, 96

Roelfsema, R., Bazzon, A., Schmid, H. M., et al. 2014, Proc. SPIE, 9147, 91473W

Sallum, S., Follette, K. B., Eisner, J. A., et al. 2015, Nature, 527, 342

Soummer, R., Pueyo, L., & Larkin, J. 2012, ApJL, 755, L28

Stark, C. C., Schneider, G., Weinberger, A. J., et al. 2014, ApJ, 789, 58

Wahhaj, Z., Koerner, D. W., Backman, D. E., et al. 2005, ApJ, 618, 385