Prediction of the planet yield of the MaxProtoPlanetS high-contrast survey for H-alpha protoplanets with MagAO-X based on first light contrasts

Close, Laird, Males, Jared, Long, Joseph, Van Gorkom, Kyle, Hedglen, Alexander, et al.

Laird M. Close, Jared Males, Joseph D. Long, Kyle Van Gorkom, Alexander D. Hedglen, Maggie Kautz, Jennifer Lumbres, Sebastiaan Y. Haffert, Katherine Follette, Kevin Wagner, Kelsey Miller, Daniel Apai, Ya-Lin Wu, Olivier Guyon, Lauren Schatz, Alex Rodack, David Doelman, Frans Snik, Justin M. Knight, Katie Morzinski, Victor Gasho, Christoph Keller, Logan Pearce, Alycia Weinberger, Laura Pérez, René Doyon, "Prediction of the planet yield of the MaxProtoPlanetS high-contrast survey for H-alpha protoplanets with MagAO-X based on first light contrasts," Proc. SPIE 11448, Adaptive Optics Systems VII, 114480U (13 December 2020); doi: 10.1117/12.2561677

Event: SPIE Astronomical Telescopes + Instrumentation, 2020, Online Only

Prediction of the planet yield of the MaxProtoPlanetS high-contrast survey for H-alpha protoplanets with MagAO-X based on first light contrasts

Laird M. Close[a], Jared Males[a], Joseph D. Long[a], Kyle Van Gorkom[a,b], Alexander D. Hedglen[a,b], Maggie Kautz[a,b], Jennifer Lumbres[a,b], Sebastiaan Y. Haffert[a], Katherine Follette[f], Kevin Wagner[a], Kelsey Miller[e], Daniel Apai[a], Ya-Lin Wu[g], Olivier Guyon[a,b,c,d] , Lauren Schatz[a,b], Alex Rodack[a,b], David Doelman[e], Frans Snik[e], Justin M. Knight[a,b], Katie Morzinski[a], Victor Gasho[a], Christoph Keller[e], Logan Pearce[a], Alycia Weinberger[h], Laura Pérez[i], René Doyon[j]

[a]Steward Observatory, University of Arizona, USA
[b]James C. Wyant College of Optical Sciences, University of Arizona, USA
[c]Subaru Telescope, National Astronomical Observatory of Japan
[d]Astrobiology Center, National Institutes of Natural Sciences, Japan
[e]Sterrewacht Leiden, Universiteit Leiden, The Netherlands
[f]Amherst College, MA, USA
[g]National Taiwan Normal University, Taiwan
[h]Carnegie Institution, Washington DC, USA
[i]Universidad de Chile, Chile
[j]Université de Montréal, Canada

ABSTRACT

Our past GAPplanetS survey over the last 5 years with the MagAO visible AO system discovered the first examples of accreting protoplanets (by direct observation of H-alpha emission). Examples include LkCa15 b (Sallum et al. 2015) and PDS70 b (Wagner et al. 2018). In this paper we review the science performance of the newly (Dec. 2019) commissioned MagAO-X extreme AO system. In particular, we use the vAPP coronagraphic contrasts measured during MagAO-X first light. We use the Massive Accreting Gap (MAG) protoplanet model of Close 2020 to predict the H-alpha contrasts of 19 of the best transitional disk systems (ages 1-5 Myr) for the direct detection of H-alpha from accretion of hydrogen onto these protoplanets. The MAG protoplanet model applied to the observed first light MagAO-X contrasts predict a maximum yield of 46±7 planets from 19 stars (42 of these planets would be new discoveries). This suggests that there is a large, yet, unexplored reservoir of protoplanets that can be discovered with an extreme AO coronagraphic survey of 19 of the best transitional disk systems. Based on our first light contrasts we predict a healthy yield of protoplanets from our MaxProtoPlanetS survey of 19 transitional disks with MagAO-X.

Keywords: adaptive optics, wavefront sensing, wavefront control, coronagraphs, high contrast imaging, exo-planets, H-alpha, protoplanets

---

Further author information: (Send correspondence to E-mail: lclose@as.arizona.edu)

Adaptive Optics Systems VII, edited by Laura Schreiber, Dirk Schmidt, Elise Vernet, Proc. of SPIE
Vol. 11448, 114480U · © 2020 SPIE · CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2561677

1.0 INTRODUCTION

A very detailed introduction to the history of the detection of Hα planets (true accreting protoplanets) is given in Close (2020)[1]. As is noted in Close (2020) Hα is a very difficult wavelength for robust, high Strehl correction due to its rather blue wavelength (most AO systems can't work where $\lambda<1\mu m$). Close (2020) finds that the sensitivity of all past searches for Hα planets with these older AO systems were only sensitive enough to detect only the most widely separated Hα planets in the largest traditional disk gaps (for a review of Transitional disks see Francis & van der Marel 2020[2]; hereafter FVDM[2]). Indeed HD142527, Lk Ca 15 and PDS 70 are among the 3 largest (>70 au) disk gaps known (only AB Aur is bigger at 156 au; FVDM). So it was quite a successful "census" in that we proved in our prior work that: 1) We can directly observe Hα from the accretion process of building planets; 2) extinction from dust doesn't extinguish this Hα emission along the line of sight; 3) Hα planets are located in, at least some of, traditional disk gaps; 4) The largest of these gaps (HD 142527; LkCa 15; PDS 70) all had detectable Hα companions in the gaps. All these results point to an incredibly exciting opportunity to discover a much more complete (and rich) sample of "hidden" forming planets if we simply can use a more modern AO system (like MagAO-X) with a coronagraph at Hα. To date none of this Hα work has been done with a coronagraph.

But some readers maybe thinking – could JWST do this work? No, it is very hard for NIRISS's AMI mode (and impossible for NIRCAM) to detect these planets at ~10 au since all these ~1-5 Myr old stars are at ~120 pc (subtending very small angles of ~80 mas from their TTauri star). Moreover, due to the limited nature of JWST's $\pm 5^o$ roll angle, it will require extensive PSF calibration and observing time to build contrasts $>10^{3-4}$ with the AMI mode (which blocks 85% of JWST's aperture/throughput) to distinguish protoplanetary disks from PSF noise at ~80 mas[3]. Hence such blind AMI searches will require at least ~4 hours per star for all PSF calibrations, overheads etc. It would require ~144 hours of JWST "blind" searches to survey the known 36 large disk gaps and it would still miss all of these planets at <80 mas separations. It is critical to discover these planets first with AO, and then only the widest best cases could be attempted with JWST follow-up observations.

1.1 Collecting the First Large Sample of Protoplanets

We are trying to address the well-known exoplanet science problem of "low-yield" of direct imaging surveys of self-luminous planets. While large H-band surveys with GEMINI/GPI and VLT/SPHERE resulted in <1% planet yields[4], we conservatively predict planet yields from MaxProtoPlanetS as >50%. Our trifecta recipe for success is by: 1) Looking in the largest disk gaps at the wavelength where the planets are brightest (Hα); 2) when they are brightest (<5 Myr); and 3) utilizing the world's first coronagraphic Hα extreme AO system (MagAO-X). Moreover, H-band 10-200 Myr old star surveys are only sensitive to very rare "hot-start" planets, yet our Hα survey can also be sensitive to the, likely more common, "cold-start" planets during their very bright accretion phase[1].

2.0 Directly Detecting Protoplanets

2.1 MagAO-X: A New Level of Wavefront Control in the "Visible AO" Era in Astronomy.

Previously with the first large D≥6.5m visible AO system (MagAO; PI L. Close) we achieved Hα contrasts of 10^{-3} at 0.2" arcsec from a bright star (Wagner et al. 2018) as we detected the in-fall of hydrogen gas as it accreted onto low-mass companions in the cleared gaps of transitional disks[5,6,7]. Then Haffert et al. (2019) [8] used VLT/MUSE AO system to confirm PDS 70 b and discover PDS 70 c at Hα.

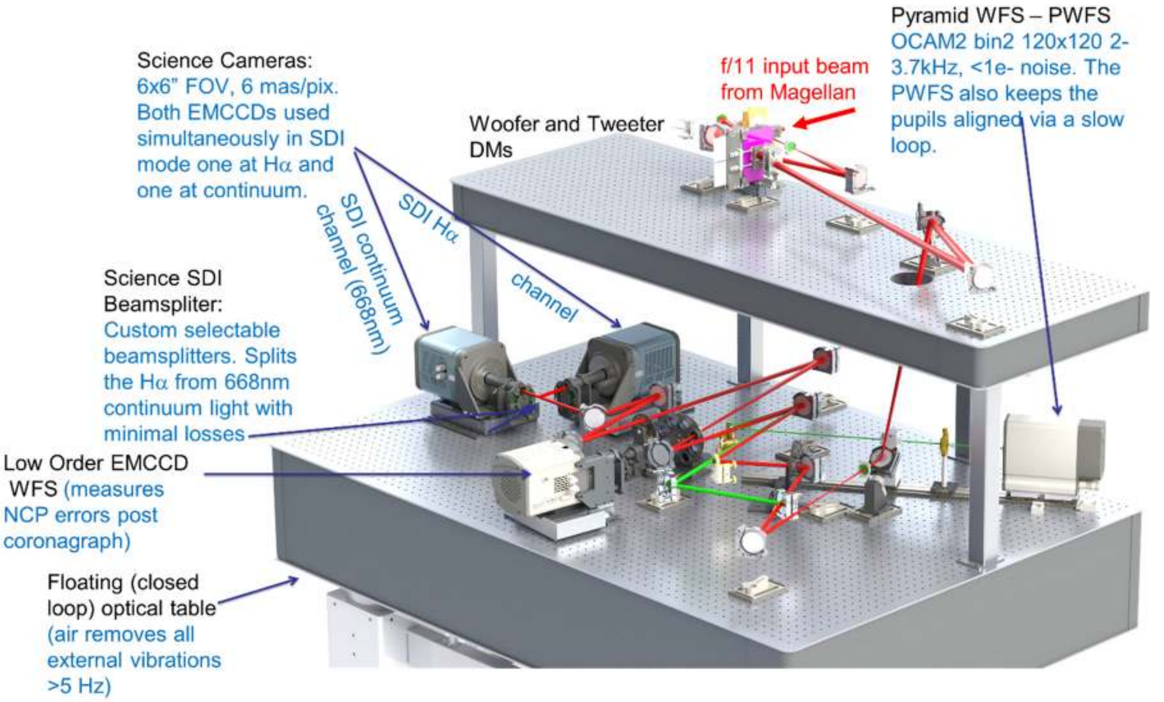

Fig. 1: Overview of MagAO-X. The woofer and tweeter DMs are on the upper bench. See Males et al. 2020[11] for more details about MagAO-X. Figure modified from Close et al. 2018[10].

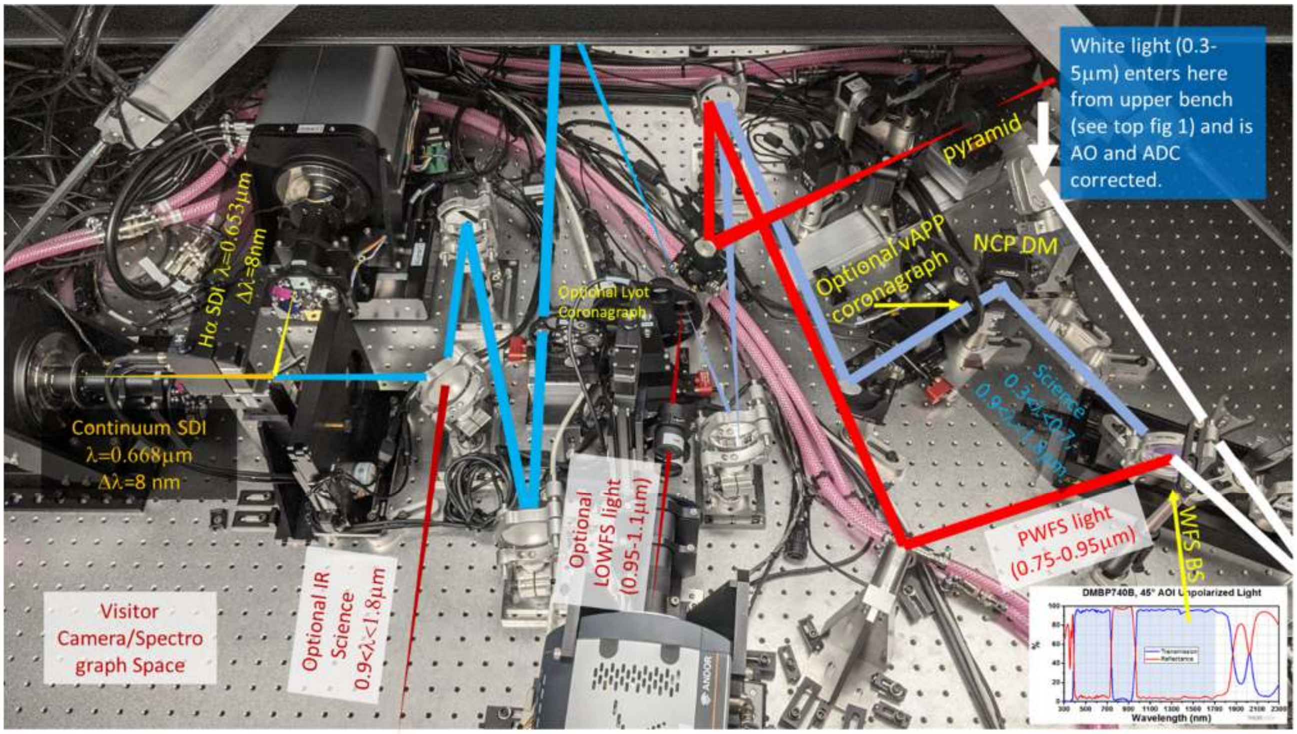

Fig. 2: A photo (Dec 6, 2020) of the lower bench of MagAO-X showing the Hα SDI configuration. Either the vAPP coronagraph[14] or the Lyot coronagraph[11] can be selected. Note how the two SDI science cameras (far left) simultaneously record Hα and continuum coronagraphic images. Some light (0.95-1.05 μm) can be used by the LOWFS EMCCD for rapid tip-tilt guiding or pupil viewing.

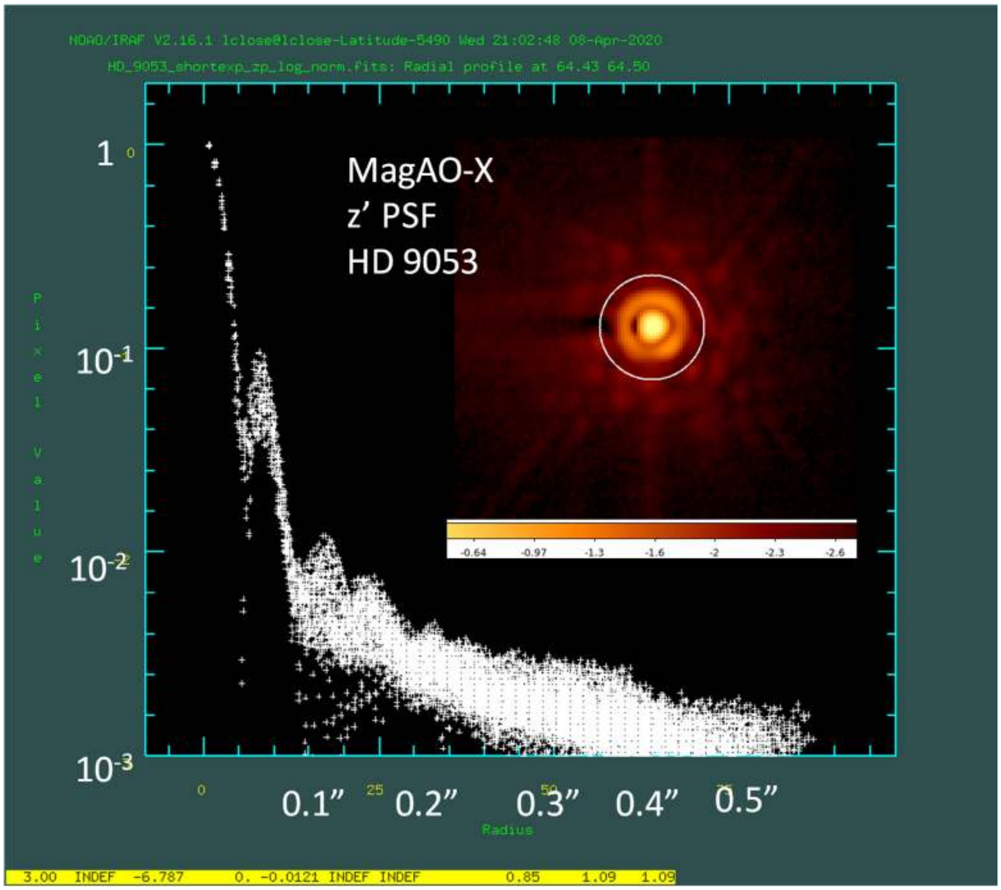

Fig 3: First light MagAO-X PSF. An example of how with MagAO-X's excellent correction (Strehl 46% at z';120 nm rms residual wavefront error WFE) and visible science EMCCD we can achieve good correction in typical 0.7" seeing. White circle is at 0.1" radius. In Fig 4 we show the coronagraphic PSF with higher contrasts.

These impressive "Hα AO" detections were done with older AO systems (SPHERE/MUSE, MagAO) with relatively low (<10%) Strehls at Hα. However, we have just had first light with the world's newest extreme AO system MagAO-X. MagAO-X is unique (see figures 1-2) --it was designed from the start to work in the visible at high Strehl[9,10,11]. Developed by an NSF MRI Grant, (PI Jared Males) MagAO-X yields a superior level of wavefront control with a 2040 actuator Tweeter deformable mirror (DM) and a unique "extra" DM to eliminate all Non-Common Path (NCP) errors between the science and wavefront sensing channels, minimizing coronagraphic leak. Wavefront sensing (WFS) with MagAO-X's very low noise (<0.6 rms e- read noise) EMCCD pyramid WFS detector allows Strehls of 50% to be obtained while closed loop at 2kHz (residual WFE <120nm rms – as demonstrated on-sky see Fig. 3). The low noise of this sensor allows good correction even on faint R~13 mag guide stars in good 0.5" seeing conditions. The MagAO-X system with up to 1500 corrected modes maps to ~15 cm/actuator, making it the highest sampled AO system in the world. Please see Males et al. (2020) [11] for more information about the successful first light run (Dec. 2019) with MagAO-X. Unfortunately, we have not been able to make any MagAO-X observations in 2020A or 2020B due to COVID-19 restrictions. Luckily during 2020

MagAO-X has been in the lab at the University of Arizona and has been upgraded to double the throughput at Hα with a custom beamsplitter and an optional Lyot coronagraph was added (see fig 2). The alignment of the PyWFS camera lens was automated and improved (see fig 1).

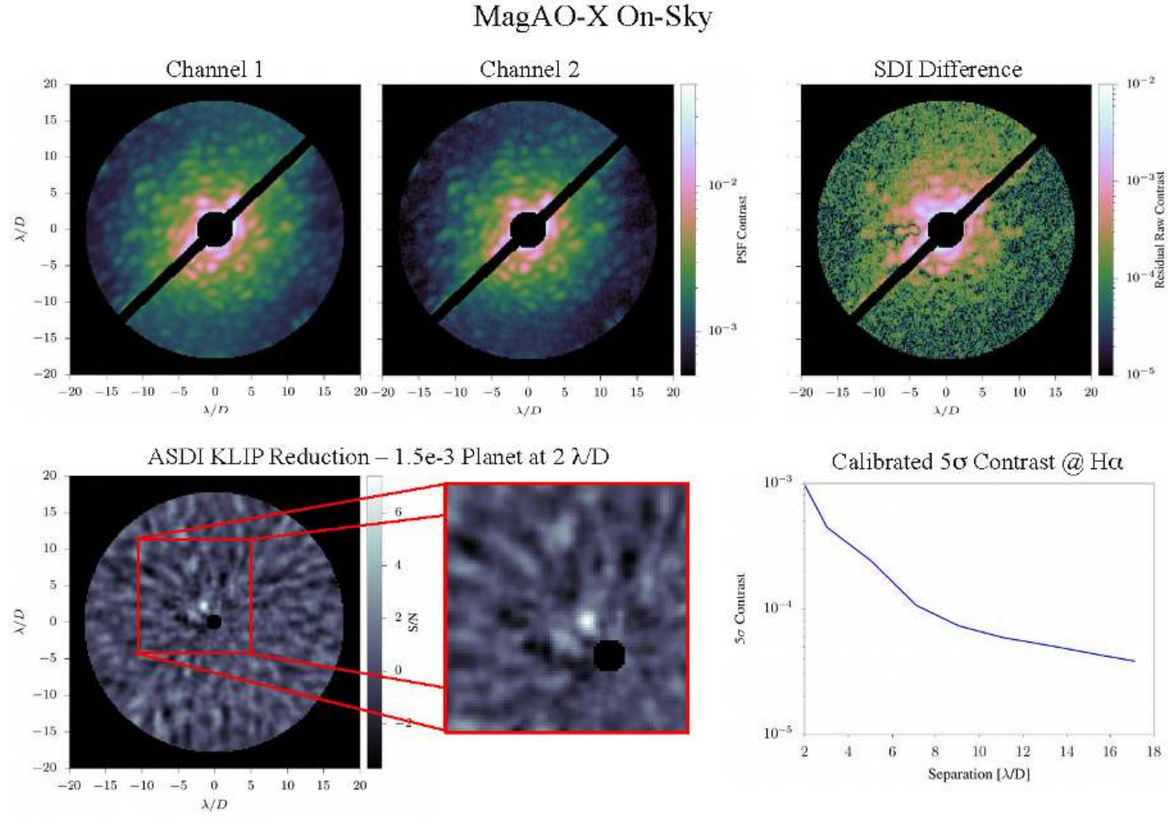

Fig. 4: Top Left: Two hour stacked SDI coronagraphic integrations on Beta-Pic. The cameras make a Channel 1 (Hα) and a CH 2 (continuum) image (fig 2). The CH 2 speckles subtract well from CH 1 (SDI image, *right*). ***Bottom:*** Principal Component Analysis (PCA+KLIP; Males et al. 2014a) pipeline produces very high-contrast images. Here CH 1=875nm and CH 2=925nm. CH 1 is not Hα due to no deep Hα data being available from the short 0.5 "science" night part of the first light run (unfortunately MagAO's 2020A run was cancelled due to COVID-19). However, the Hα contrast curve is correctly, conservatively, degraded for 656.3nm (Hα)--rigorously tested by recovery of inserted fake Hα planets (where 2λ/D=42mas). For more on reduction see Males et al. (2020) [11].

2.1.1. MagAO-X's Special SDI Hα Mode: Spectral Differential Imaging at Hα

To enable high-contrast AO one needs simultaneous exact PSF information to compare to (or subtract from) the Hα emission line science image. An extremely effective technique for this is Simultaneous/spectral Differential Imaging (SDI) (Marois et al. 2000[12]; Close et al. 2005[13]; first used at Hα by Close et al. 2014[5]). The MagAO-X coronagraphic SDI cameras work by first removing the diffraction rings of the PSF with a vector Apodised Phase Plate (vAPP) coronagraph. It apodizes the wavefront in the pupil plane, so no loss in performance due to PSF jitter, nor is there any loss in ang. resolution[14]; the remaining speckles in the "dark hole" are very stable (see Fig 4) and can be scaled and PCA pipeline subtracted to reveal Hα planets at just ~2λ/D (~42mas) by removing starlight speckles.

The throughput of the MagAO-X SDI mode is ~200% higher than that of ZIMPOL and >400% higher than MagAO due to use of a special custom dichroic SDI beamsplitter cube that reflects the Hα light (656.3nm; 8nm bandpass) to CH 1 and transmits the continuum (668 nm; 8nm bandpass) to CH 2, and a custom dichroic that passes all the Hα light to the cameras and then reflects the rest to the WFS (fig. 2). We have further optimized our SDI sensitivity by developing very special matched layer/single (no-ghosting) narrowband filters. As can be seen from Fig 4 there is no obvious WFE between the Hα and continuum images. The cube beamsplitter SDI optical design minimizes (<1%) the differential polarized intensity which is removed in data reduction with a simple ~0.99 intensity scaling correction. The ASDI/KLIP pipeline data reduction products are shown in Fig. 4.

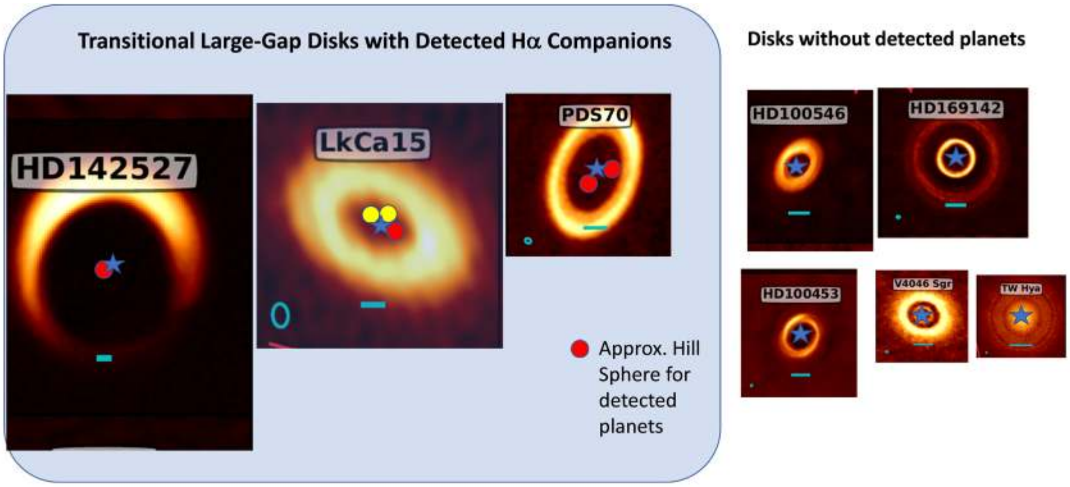

Fig. 5: Big ALMA cavities yield multiple gap planets. Early Hα SDI results include the exciting detections of HD142527B[5], LkCa 15b[6] and PDS 70b[7] and PDS 70c[8]. The upper images are from ALMA reproduce from FVDM (blue horizontal bar = 30au). Directly beneath each ALMA image is the same system seen with AO in scattered light. Note HD142527 is not to scale as it would not fit. Figure modified from Close et al. 2020[1] .

3.0 The MaxProtoPlanetS Survey

SCIENCE GOALS OF MaxProtoPlanetS:

1) Discover, by direct imaging, young accreting exoplanets down to ~0.5 M_{jup} and measure their Hα emission and estimate the accretion luminosity.

2) Determine the frequency and distribution of young (~1-5 Myr) actively-accreting giant planets on ≥4-40AU orbits around all 19 nearby (~50-180pc) TTauri stars with large (20-80 au) gap transitional disks.

3) Determine how these Hα planets are located w.r.t. the disk structures – *do they actually sculpt the gap edges? Cause spiral arms? Is multiplanet planet "wide gap" clearing MAG theory correct?*

4) Measure the accretion luminosities ($L_{H\alpha}$, L_{acc}) due to gas delivered by accretion onto the protoplanet. Do they accrete ~10% or ~50% of the star's accretion?

5) For each "protoplanet" discovered, **we will simultaneously photometrically characterize the Hα and 668 nm continuum (or set continuum upper limits). Then later, in follow-up, obtain Hβ (486.1nm) strengths.** This will allow estimates of the true dust extinction (from ΔHα/ΔHβ ratio and a rough planet SED model), which in turn allows a dereddened Hα line flux to be calculated from equation (1). Then the accretion luminosity (L_{acc}) and mass accretion ($\dot{M}_p$) can be estimated as we did in Close et al. 2014[5]; Sallum et al. (2015) [6]; and Wagner et al. (2018) [7]. Protoplanet masses can also be estimated from equation (2), or if the $\dot{M}_p$ is very low from equation (3). Our extinction estimates can be sanity checked with HST "u" band imaging of the widest targets.

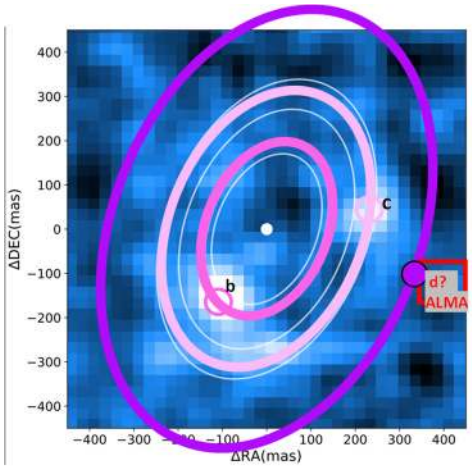

Fig 6: Hα image of PDS70b, c (Haffert et al. 2019). The predicted inner (a_1=0.30Rcav) and middle (a_2=0.47Rcav) orbits from our MAG model applied to the Rcav=74au PDS70 cavity/gap. The open circles show the predicted planet positions (PA is fit to the planets). Excellent agreement with observation. Planet "d" is hinted at by an ALMA detection (red box). We can't detect outer planet d at Hα due to the disk's inclination (see red line Fig 7).

3.1 Past Work Detecting Protoplanets

3.1.1. Proof of Concept: The PDS 70 system

As figure 5 shows there are a handful of very large gaps known. It is interesting to note that in *every* case of a very wide gap there was an accreting companion discovered inside the gap[1]. An excellent example is the PDS 70 system. PDS 70 A is a 0.8M_{sun} TTauri star of age 5Myr accreting at ~6x$10^{-11}M_{sun}$/yr (Hashimoto et al. 2020[15]), which has a spectacularly large 74 au wide gap (see Fig 5). Imaging with SPHERE was able to discover thermal emission from the disk and atmosphere around the gap planet PDS 70b (Keppler et al. 2018[16]). We were able to use MagAO to discover Hα from magnetospherical accretion onto PDS 70b[7]. We were also able to use the VLT's MUSE IFU to confirm the Hα emission from PDS 70b and discovered PDS 70c as another Hα protoplanet inside the gap (Haffert et al. 2019[8]; see Fig 5.). Since the separations of PDS 70b and c are rather large (0.19" and 0.23" respectively) large telescopes like KECK at L' (3.8um) are able to follow-up these planets to detect their circumplanetary disk emission (Wang et al. 2020[17]) where the masses of the planets are measured to be roughly 2-4M_{jup} for b and ~1-2M_{jup} for c. In a similar manner JWST could image the circumplanetary disks of the Hα planets discovered by MaxProtoPlanetS.

3.1.2. But won't the dust from the star's accretion disk absorb all the Hα emission?

In transitional disks, whose dust cleared central cavities are optically thin, there is little extinction towards the protoplanet. This is especially true for the polar regions of the planet where the Hα is created by the shock from the magnetospherical accretion. In fact, it has been theorized that the reason these gaps stay dust free is due to the sculpting influence of giant planets (Alexander & Armitage 2009[18]). The best MaxProtoPlanetS candidates are the so-called "wide gap" transitional disks that may need multiple >1 M_{jup} mass planets to keep the gap cleared, since these gaps are >5x the size of any one planet's Hill sphere:

R_H=33/40(a/10)$(Mp/M_*)^{1/3}$ au; where Mp is the mass of the planet in M_{jup} and M_* is the mass of the star in solar masses. Hence even a massive 5 M_{jup} planet can only open a ±6 AU gap at a=10 au in 10 Myr (according to the hydrodynamical simulations of Dodson-Robinson & Salyk 2011[19]). The popular "gap planets" theory of [19] makes a convincing case that multiple (3) massive (3 M_{jup}), co-planar, gas planets can produce all of the commonly observed properties of transitional disks, including large gaps. Such gap planets scatter the dust creating the observed gaps --but let the gas pass through the gap. Some gas accretes onto the planets and the rest onto the star. This allows for long lived (1-5 Myr) gaps around continuously accreting TTauri stars. These timescales fit the observations (Fig. 5,6) much better than the competitor "photoevaporation" theory where once a large gap is cleared, the theory predicts accretion onto the star quickly ends. There are too many large gaps over a large age range (1-10 Myr) for photoevaporation to explain all these features (see the review of Owen 2016[20] and references within). But we should also be open to the question: if gap planets clear all these cavities, why have we not observed Hα planets in *all* of these cavities (Brittain et al. 2020) [21]? In the next few sections we will try to address that question.

By targeting transitional disks that are not exactly edge-on (see Fig. 5 for examples). We should be able to directly detect Hα produced by gas orbiting across the gap onto the planet (or onto a shock surface/boundary) without high extinction along the line of sight.

3.2 Filling in the Gaps: A New "Massive Accreting Gap" (MAG) Protoplanet Model

The model of Dodson-Robinson & Salyk (2011) [19] (herein the DRS model) has continued to be the most common explanation for these large gaps in the literature. However, there are a few inconsistencies with observational data. For example, DRS predicts that all the gap planets have the same mass, implying that all gap planets would be equally bright at Hα and other wavelengths. There is evidence that this is not the case, for example, PDS 70 c (outer planet) is roughly 50% the mass of inner planet PDS 70b[17], similarly HR8799b (outer planet) is roughly 50-70% the mass of inner planet HR8799[22-23]. Also, the DRS model claims there must be a large massive planet with $4R_H$ of the cavity edge (Rcav). In fact, detailed modeling by Dong & Fung (2017) [24] showed that the optical scattered light edges (like those in Fig 5) showed signs of being sculpted by outer planets of masses no more than ~1 M_{jup}. Also, the long term stability of the DRS model was questionable past 10 Myr given that the planets were all massive but were not in a stable mean motion resonance (MMR). Nature prefers an MMR configuration for stability with massive planets. Our best example of a massive multiplanet system is the HR8799e,d,c,b set of 4 massive (5-10 M_{jup}) planets spanning over 70 au. We have been observing this system long enough to be able to fit this with a classic 1:2:4:8 MMR that allows long term stability (see Gozdziewski & Migaszewski 2014) [25].

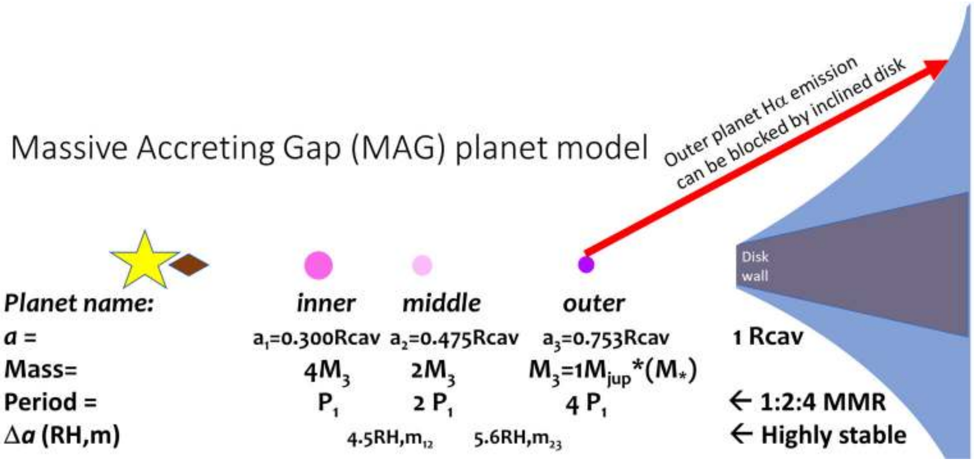

Fig 7**: A cartoon of the MAG model of gap planets.** This model satisfies the following: 1) overlapping ≤$4R_H$ sectors to be dust-free to Rcav; 2) dynamically stable: 1:2:4 MMR; 3) Each planet, pair-wise, has a separation of at least 2√3 mutual Hill Radii ($R_{H,m}$); to be stable>>10Myr; 4) outer planet $4R_{H3}$ from Rcav to create dust-free edge.

We have just published a significant theoretical Astronomical Journal manuscript that fully explores the idea of what type of population of massive accreting gap (MAG) planets would be needed to clear (and keep clear) the large gaps observed in many transitional disks. We note that Close (2020) [1] contains full derivations of all equations, detailed explanations, and estimates of uncertainties for masses, orbits, and contrasts predicted by the MAG model. In the next sections we will highlight the important aspects of the MAG model, but we note that the reader could look at Close (2020) [1] for additional depth if desired.

We can build on strengths of the DRS model with a new MAG model. In the MAG model we make only 2 assumptions. The first MAG assumption is that all three planets in the gap are in a stable 1:2:4 MMR ($a_1=a_2/2^{2/3}$; $a_2=a_3/2^{2/3}$). This is the most natural stable configuration for the system to evolve into as the planets all migrate inwards. Mechanisms of MMRs formation are widely studied as the result of planetary migration (see a review by Papaloizou & Terquem 2006[26], and references therein). As soon as this migration starts the planets open their individual gaps and then produce one large gap since their individual $4R_H$ clearing zones overlap. At this point the inwards migration nearly stops, and the orbits are stable and "locked" in the MMR (see for example figure 5 of Gozdziewski & Migaszewski 2014) [25]. The second MAG assumption is that the mass of the inner planet is half that of the middle planet which, in turn is half that of the inner planet ($M_2=M_1/2$; $M_3=M_2/2$) to be compatible with current observations as noted above.

In an MMR there must be $(2^{5/3}+2^{7/3}+2^3)R_{H3}$ across the distance from the star to the cavity edge (Rcav) since a_3 is exactly $4R_{H3}$ from the cavity edge (to keep it clear of dust). So $Rcav-4R_{H3} = a_3 = (2^{5/3}+2^{7/3}+2^3-4)R_{H3}$. Therefore, $a_3=(2^{5/3}+2^{7/3}+2^2)/(2^{5/3}+2^{7/3}+2^3)=0.75Rcav$ for all cavities in the MAG model. That means $a_2=0.47Rcav$, and $a_1=0.30Rcav$ in the MMR.

Since the outer planet is $4R_{H3}$ from the edge of the gap (Rcav), there must a certain mass for M_3 to achieve this, we see:

$R_{H3} = (Rcav-a_3)/4 = 33/40(a_3/10)(M_3/M_*)^{1/3}$ au, but substituting $a_3=0.75Rcav$ yields:

$M_3/M_* = [1600/(99(2^{5/3}+2^{7/3}+2^3))]^3 = 0.99$, so $M_3 = 0.99(M_*/M_{sun})$ in units of M_{jup} (the more massive the star the more massive the planets). The MAG model has no free parameters w.r.t. the orbits: outer separation is $sep_3=0.75Rcav[1+((2-\pi)/(\pi)1-\cos(\mathit{disk\_inclination}))]/D$ arcsec (an average projected separation on-sky). Fig 7 is a cartoon of the MAG model. We note that MAG predicts the observed orbits of PDS70b and c (and maybe d) very well (see Fig 6).

How does MAG explain planetary Hα emission? Hydrogen will "seek out" any gravitational potential wells (planets) on its slowly decaying orbit around the star – and these wells (planets) will emit in Hα as a fraction of the gas magnetospherically accretes from the circumplanetary disk onto the high polar regions of the planets. A detailed physical model of this explains PDS70b's Hα emission in detail (Thanathibodee et al. 2019)[27]. This model predicts a mostly dust-free l.o.s. and significant Hα observed for the small (~2-4M_{jup}) planets like PDS 70c,b in agreement with the 3D thermo-hydrodynamical models of Szulagyi et al. 2020[28], but only in their "gas only" case --this case is the only one of their models that matches observations of PDS 70 b and c.

3.3 Extinction: How do we estimate how much Hα is Extincted?

These gaps are very well cleared of dust (especially around the inner planets) minimizing extinction. The extinction towards the star is well known for all 19 of our targets (see Table 2; Close 2020) [1]. However, there can be, in theory, extra extinction towards the planet's Hα emitting polar regions. We note that for the MaxProtoPlanetS survey we will obtain Hβ vAPP coronagraphic images for follow-up. Comparing our observed $\Delta H\alpha/\Delta H\beta$ flux ratio to our "theoretical" recombination model from Hummer & Storey (1987), and a rough planetary SED model to estimate the ratio of the continuum Hα/Hβ, we will have a direct measure of the extinction at Hα for the gap planet detected (this is similar to the extinction estimation technique of Close et al. 1997) [29].

3.4. Hα Line Luminosity Calculation: Detailed Example of PDS 70 b

As is already published in Close 2020[1] and utilized in [7] the $L_{H\alpha}$ luminosity can be calculated for a gap planet (PDS 70b) by:

$L_{H\alpha}=4\pi D^2*vega\_zero\_point\_calibration*filter\_width/10^{(\text{deextincted vega magnitude of b at H}\alpha)/2.5}$

where the magnitude for b at $H\alpha= R_A+\Delta magH\alpha-A_R-(2.5\log(\text{flux }H\alpha/\text{flux continuum}))$

Therefore, $L_{H\alpha}$ can be written:

$$L_{H\alpha}= (4\pi D^2)Vega\_0\_\ H\alpha\ \_c*Filter\_width\ /(10^{((R_A+\Delta magH\alpha-A_R-0.25)/2.5)}) \qquad \textbf{(1)}$$

$\mathrm{Log}(L_{H\alpha}/L_{sun})=\log(4\pi(113*3.1\text{x}10^{18})^2*2.34\text{x}10^{-5}*0.006/[3.9\text{x}10^{33}*10^{((11.696+(7.36\pm0.47)-0.2-0.25)/2.5)}]=$ 5.70 ± 0.19 where the Vega zero point magnitude in our Hα filter (Vega_0_ Hα _c; see Males et al. 2014[30] for the zeropoint calibrations) is calculated to be $2.339\text{x}10^{-5}$ ergs/(s cm^2 µm). This a significant amount of emission and almost 10x better contrast than at H band[16]. We note that PDS 70c is almost undetectable at H band (Mesa et al. 2019), but quite detectable at Hα (Haffert et al. 2019) [8]. Therefore, an SDI survey in Hα will be very sensitive to very low mass gap planets.

Since low mass, young, objects have Xshooter calibrated accretions rates (Rigliaco et al. 2012) [31] we find $L_{acc} = 10^{[2.99\pm0.23+ (1.49\pm0.07)*(\log(LH\alpha))]}$ from the empirical L_{acc} to $L_{H\alpha}$ relations of [31] for very low mass accretors. However, Thanathibodee et al. (2019) [27] find, by direct simulation of the gap planet accreting process, that weakly accreting planets accreting with $\dot{M}p<5\text{x}10^{-12}M_{sun}/yr$ (similar to PDS 70b) are better fit with a $L_{acc} = 10^{[-3.62+0.353\log(LH\alpha)]}$ power-law. Which yields a lower accretion luminosity (L_{acc}) for PDS 70b of $\log(L_{acc}/L_{sun})=-5.63\pm0.18$. Then using the standard accretion relation:

$\dot{M}p = 1.25L_{acc}R_p/(GM_p)$ of Gullbring et al. (1998) [32], yields a planetary accretion rate of $\dot{M}_p=5\text{x}10^{-12}\ M_{sun}/yr$ (using M_p mass estimate of ~4 M_{jup} for PDS 70b[17]). Planet radii are from 5 Myr COND exoplanet evolutionary models with an estimate of $R_p=1.3R_{jup}$.

This planetary accretion rate is $5\text{x}10^{-3}\ M_{jup}/Myr$ which suggests the ~5Myr planet is at the end of its accretion phase. But even in this rather weak accretion flow, the Hα emission allowed both b and c to be detected. This planetary accretion rate is also equal to ~10% of PDS70A's mass accretion rate $\dot{M}_* \sim 6\text{x}10^{-11}\ M_{sun}/yr$[15]. Therefore, we will adopt 10% as an estimate of the amount of the stellar accretion that is captured by a gap planet in the MAG model. Lubow et al (1999) [33] predicts the gas capture rate could be as high as 50%. So, our predicted Hα flux may be on the faint/conservative end of the range.

3.5. MAG Protoplanet Population Predictions: Case of the "Best AO Observed Disks"

The MAG model can predict the planet/star contrast (Δmag at Hα) from the work above.

In the high accretion case ($\dot{M}_*>5\text{x}10^{-11}M_{sun}/yr$) we can show from (1) and the $L_{acc} = 10^{[2.99\pm0.23+ (1.49\pm0.07)*(\log(LH\alpha))]}$ relations of Rigliaco et al. (2012) [31] that (in cgs units):

$$\Delta magH\alpha = -1.675*[\log M_p+\log\dot{M}_p-\log R_p]+A_R-R_A+5\log D+67.9\ , \qquad \textbf{(2)}$$

but if weak accretion ($\dot{M}_*\leq5\text{x}10^{-11}M_{sun}/yr$) then $L_{acc} = 10^{[-3.62+ 0.353\log(LH\alpha)]}$; so

$$\Delta magH\alpha = -7.08*[\log M_p+\log\dot{M}_p-\log R_p]+A_R-R_A+5\log D+258.22\ , \qquad \textbf{(3)}$$

Where: Mp is the mass of the planet (from MAG model), $\dot{M}p=0.1\dot{M}_*$ ($\dot{M}_*$ from FVDM); planet radius R_p from DUSTY models; extinction towards the star A_R from FVDM; the R band (R_A) magnitude of the star from SIMBAD, and the distance D (in pc) to the star from FVDM. Therefore, it is straightforward to take the 9 most well AO observed at Hα stars and predict which systems should have been detected and which are still too faint/close-in to be detectable with today's AO systems at Hα. This is done in Fig 8 ($\Delta magH\alpha$ vs. sep).

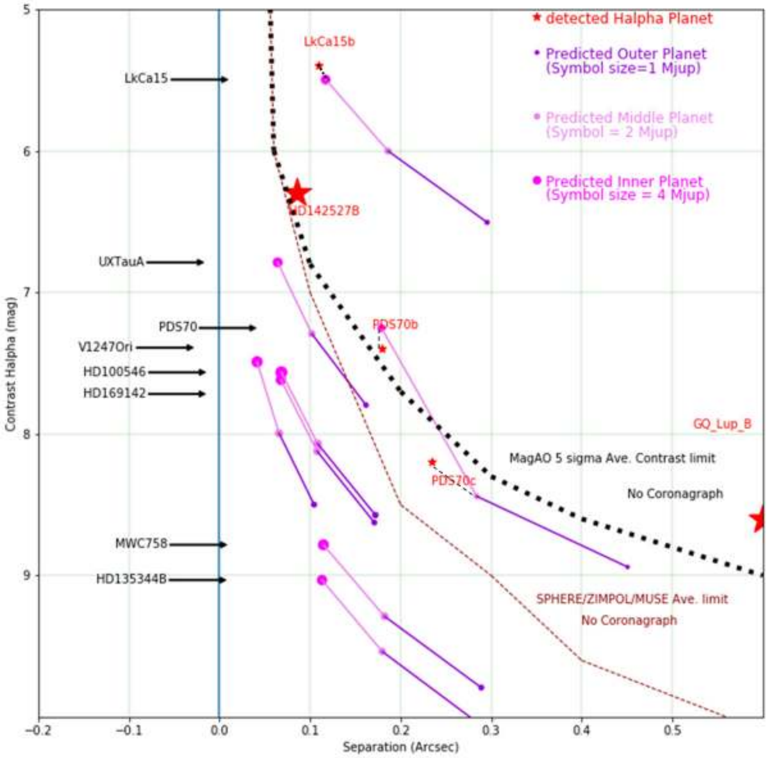

Fig 8: The MAG model applied to the most commonly observed disks. Note how well the detectable planets (*small* red stars) are predicted by MAG model (black dashed lines call out the error between model (with just average separations) and real planets). Figure modified from Close et al. 2020[1] .

The most notable point to Fig 8 is that the MAG planets that are predicted to be most easily detected (PDS 70 b, c and LkCa 15 b, c) have all, in fact, *been* detected[6,7,8] although there some uncertainty in the nature of LkCa 15c possibly being a disk feature[34], but LkCa 15 b is an Hα source and hence a true planet, and not a disk feature. However, MAG predicted outer planet “PDS 70 d” at ~0.43” has not been yet been definitively detected. Keppler et al. (2019) [35] have recently detected with ALMA a non-Keplerian (i.e. planet-like not primary disk-like; Perez et al. 2014[36]) ^{12}CO point source at 6σ. At 0.39” it is near the 0.43” MAG predicted position of PDS 70 d, moreover, at PA=260° the direct line of sight. to “d” is blocked by the disk’s 50° inclination and explains why it is not a Hα source in Fig 6. In general, Hα from the outer planet can be blocked by an inclined disk (see red arrow in Fig 7) or is not easily detected against the glare of the disk “back wall” dust clumps. The inner 2 planets are less likely to be blocked by dust extinction.

Another interesting detail of Fig 8 is that MAG predicts only PDS 70 and LkCa 15 planets are wide and low enough contrast to be detected (purple dots above black dotted line). The other 7 systems’ planets are just a bit too tight/high-contrast to be detectable with today’s Hα imagers. Since this is exactly what we observe, we can conclude that the MAG model has some predictive power. In short, we clearly need higher Hα contrasts at smaller separations --which is precisely what MagAO-X can deliver.

4.0 MaxProtoPlanetS Survey

4.1 MagAO-X Protoplanets Survey (MaxProtoPlanetS) Survey

SURVEY SUMMARY: A survey of all 20 young (~1-5 Myr), nearby (D≤180pc), bright (I≤13 mag) southerly (DEC<35°) transitional disks with large (>20 au) gaps with Hα vAPP coronagraphic SDI. *MaxProtoPlanetS is a very deep SDI survey (120 minute total open-shutter integration) around the*

19 best transitional disks with MagAO-X. This survey has been selected to receive partial funding support from the 2020 NASA eXoplanet Research Program (XRP).

4.1.1. What will be the yield of such a survey?

In Fig 9 we show the MAG model applied to the entire survey with the MagAO-X's 5σ Hα SDI contrast curve (from Fig 4). We predict a max. yield of 46 (42 new) planet discoveries from the top 19 stars (each purple dot above the blue line is a detectable gap planet by MaxProtoPlanetS).

4.3 Reality Check: *What Seeing is Required to Meet the Strehls and Contrasts Needed?*

From our "pilot" HD142527, LkCa15, GQ Lup and PDS 70 observations (Follette et al. 2021, in prep.) with MagAO and our first light run with MagAO-X we know that in ≤0.85" seeing and ≤25 mph winds we will have the required Hα Strehls and contrasts for MagAO-X**.** Hence in ~90% of the nights at Magellan we will obtain the quality of correction (≥25% Strehl at Hα; I<10 mag) needed.

4.3.1. What if There is Extra Extinction for the Planet?

Fig 8 already completely corrects for the known extinction to the star. This stellar extinction is doubled towards the planet if the scattered light image shows some signs of fine dust in the gap (HD100546, HD135344, AB Aur). We don't expect a very large issue with extra extinction since magnetospherical accretion on gap planets creates Hα at high latitudes on the planet in the dust cleared magnetically dominated part of the inner circumplanetary disk (see Thanathibodee et al. 2019[27] and references within).

4.4. Observing Plan, Epoch 1: *How much observing time is needed to survey these 19 targets?*

Our first light MagAO-X narrowband coronagraphic SDI observations prove that in 2.5 hours of telescope time (all overheads included for 2 hour open shutter integration) we can probe down to the 5σ blue curve in Fig 8 for an average target (I<11.7 mag) in median observing conditions. Our 5 faintest targets are labeled in blue colored text in Fig 9 (11.7<I<13 mag) and they each have the contrasts increased by 2.0 mag to account for the lower AO Strehls for these stars. These faint stars will be executed in better than median observing conditions (good, slow, seeing), hence the blue curve is a good guide for all our targets (6<I<13 mag) even if the contrasts will be ~2.0 mag worse at I~13 --because each faint "blue" target has been forced down +2.0 mag in Fig 9.

Therefore, we will need a total of 5 nights plus a safe 35% bad weather contingency factor equals 7 nights (7n) total (3n in the fall and 4n in the spring to cover the RA range). Since the site has a median of 0.64" seeing (Thomas-Osip et al. 2008[37]), we will have >5n of <0.8" seeing in 7n (≤0.8" seeing is optimal for MagAO-X performance; Fig 4). The Arizona TAC has already enthusiastically endorsed the MaxProtoPlanetS science case and the 2020B observing proposal submitted by PI Close received 100% of the nights requested (but was cancelled due to COVID). We are optimistic that COVID related delays will not impact the official 2020B start of the survey (the Magellan Telescope is open and operating every night now --Nov. 2020).

4.4.1. Proof that 2 hours is long enough to detect the faintest protoplanets at Hα

Do we have enough signal to detect a ΔmagHα=10 mag planet @0.1" from a R~11.7 star? Since $S/N=(planet*time)/[excess*planet*time+excess*numpix*time*(sky+SDIspeckle+dark)+readn^2]^{1/2}$ where time is the exposure time, EMCCD excess noise=2.0, numpix=9pix 0.18x0.18" patch, sky=0.0227ph/s/pix background, and the calibrated[7] ΔmagHα=10 mag planet flux is 0.0257 Hα ph/s/pix (where 35% of frames are rejected for low SR and total Hα QE is 41% --falling to ~14.5% with the vAPP). For our science camera we adopt dark=0.05e/s/pix, and readn = 0.5e- rms with

EMCCD gain. The main limiting S/N term is the SDI photon-noise from the PSF speckle floor: SDIspeckle–which is calibrated from the upper left panel of fig 4 and is ~2.57 $H\alpha$ ph/s/pix @0.1” ($5\lambda/D$) and ~0.257 ph/s/pix @0.2” ($10\lambda/D$). We find that using EMgain=500 with time=0.1s with just 30% SR AO correction yields a S/N=9.61 detection in 2 hr. on a $\Delta magH\alpha$=10 mag planet @ sep=0.2” (and S/N=4.1 @ sep=0.1”) with an R=11.7 mag guide star. Hence protoplanets from ≥0.1” with $\Delta magH\alpha \leq 10$ mag can be detected in 2 hours with the vAPP even around the faint guide stars.

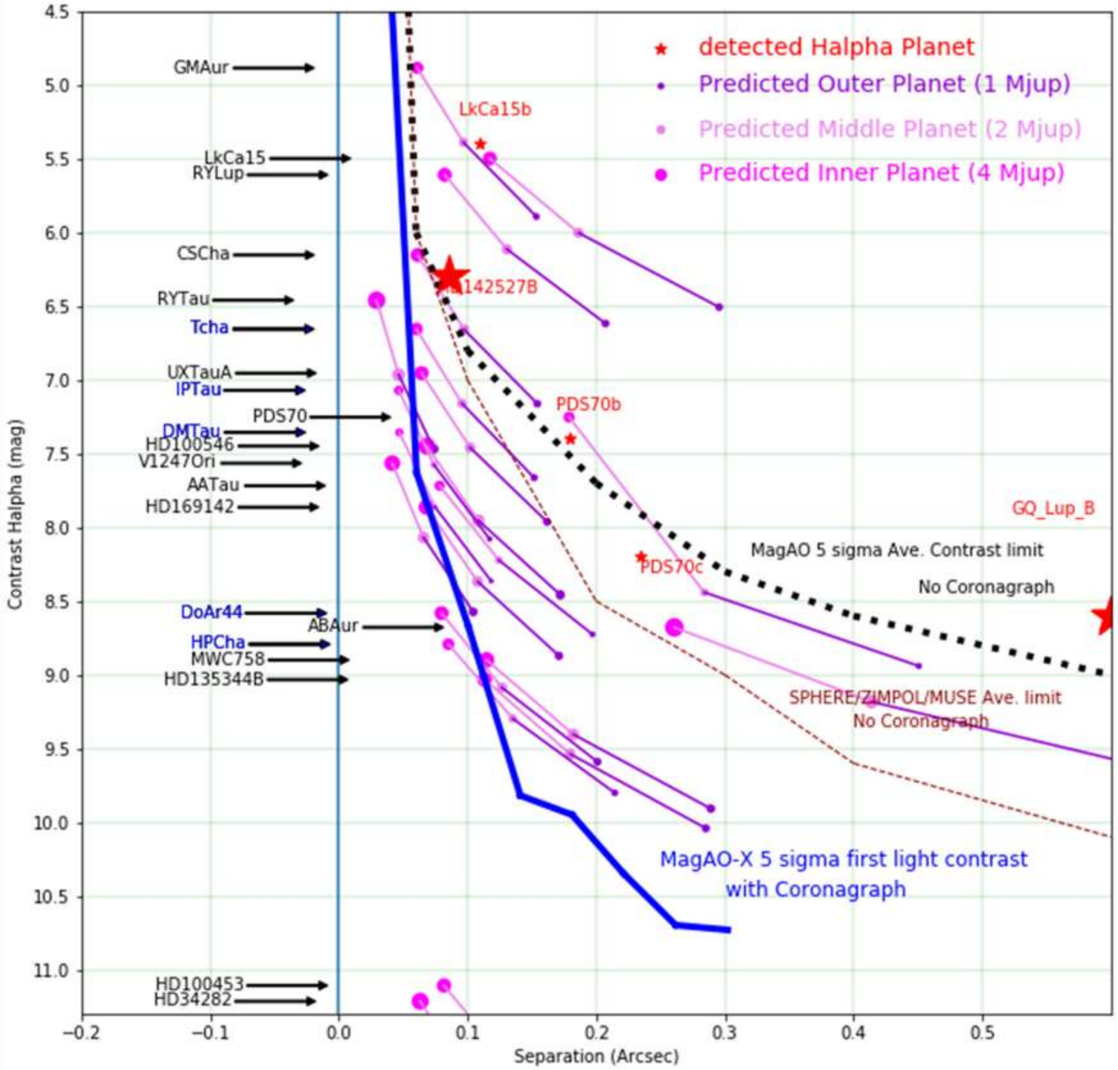

Fig. 9: The MAG planet model applied to all 25 bright (I<13) FVDM[2] single stars. The MagAO-X contrast limits from the observations of Fig 4 are plotted as the solid blue line. We can trivially see that *MagAO-X should be able to detect 46 gap planets (42 new) from the top 19 systems (all those above HD100453)*. Figure modified from Close et al. 2020[1].

4.5 Follow-up: 2nd Epoch $H\alpha$ and $H\beta$ Observations, and Planet Mass Estimation

In the second year of the survey we will finish common-proper-motion follow-up “2nd Epoch” of all faint $H\alpha$ candidates found in epoch 1 to be sure of common proper motion. If 100% of the disks have at least one candidate, then we estimate a maximum of 3n 2022B and 4n 2023A will be needed in year 2 to finish the follow-up observations. For the follow-up half the integration time (one hour open shutter) will be at SDI Hα to confirm the candidate, and 1hr at SDI Hβ will be obtained simply by rotating in the Hβ filter (and the matching Hβ continuum filter) in the SDI camera with our 50/50 beamsplitter cube. If there are fewer than the predicted 100% planet yield/star from epoch 1 then we can increase these follow-up exposure times proportionally. The 2nd epoch will also inform us about the variability of the planets at Hα.

As noted above the ratio of ΔHα/ΔHβ will be used to estimate the extinction to the planet (A_R), and then crudely estimate the $\dot{M}p$ of the planet from the published $\dot{M}_*$ of the star (by multiplication of the 10% ratio observed from PDS 70 b). Then we can simply estimate the mass of the planet from equation 2 (if $\dot{M}_* \leq 5 \times 10^{-11} M_{sun}/yr$ then equ. 3). This will only yield a crude estimate of the companion mass (M_p) but will help us differentiate between planets, brown dwarfs and stars. Also, if we detect any point source counterpart in the continuum image then we have detected a young brown dwarf (if not then it is a true protoplanet). Even in the case that the planet is very low mass (and very faint) hence only planet/star ΔHα is measured (with no detection at Hβ) – we can still estimate a range of extinctions, and hence a rough mass for each accreting planet discovered. In that "faint planet" case, we can await further detail of the circumplanetary accretion disk from future JWST follow-up by other observers.

Then in the start of year 3 we will publish the full census of MaxProtoPlanetS and place strong limits of the distribution and nature of young extrasolar planets.

4.6 What is the Expected Yield of MaxProtoPlanetS?

From Fig 9 we predict with the MAG model a maximum yield of 46±7 planets from 19 stars (42 would be new discoveries). This planet yield is robust, for example the DRS model applied to our sample would suggest a similar planet yield of ~41 planets. So, our success is not locked into the fine details of the MAG model alone. If we, very conservatively, assume that all the outer planets prove hard to detect due to extinction by the disk edge (or simply that there are only 2 planets/gap), then we have 21±5 new planets. So this survey will be productive regardless of the fine details of the true gap planet population.

4.6.1 What Would a Null Result Mean?

Even in the very unlikely case that LkCa 15b and PDS70b,c are the only gap planets in nature (a survey null result), our great sensitivity with MagAO-X to low-mass planets will allow us to place tighter constraints on the outer extrasolar population than ever before possible (for both "cold-start" and "hot-start" planets) --and such a "null" result will then reject the MAG and DRS multiplanet clearing gap models at ~5σ significance.

So, no matter the outcome, the MaxProtoPlanetS survey size is large enough that there will be a statistically significant result and a large increase in exoplanet science and our knowledge of where planets form, how they grow, and whether multiple planets carve large disk gaps.

5.0 CONCLUSIONS

Sub-mm interferometry (SMA, ALMA etc.) has detected a significant group of large (20-80 au) gaps in many transitional disks. A handful of these disks have been shown to have Hα bright companions inside them (HD142527B; Close et al. 2014; LkCa 15 b; Sallum et al. 2015; PDS 70b; Wagner et al. 2018; PDS 70c; Haffert et al. 2019), but some transitional disk AO surveys have not revealed any new gap planets (Cugno et al. 2018[38]; Zurlo et al. 2019[39]). This has encouraged recent theoretical studies which suggest Hα can be only detected from the most massive planets (>10

M_{jup}) [28] or can be highly variable[21]. But are these null results a selection effect of the AO sample selected and the limits of high-contrast AO at Hα? To answer this question requires a simulated parent population of gap planets applied to all known wide gap transitional disks.

Here, and in Close 2020[1], we have presented a massive accreting gap (MAG) planet model that ensures these large gaps are kept dust free by the scattering action of 3 co-planar planets in a 1:2:4 MMR. With few free parameters, our model is consistent with the observed separations and Hα fluxes for LkCa 15 b and PDS 70 b and PDS 70 c within observational errors. Moreover, the model suggests that the scarcity of detected Hα planets is likely a selection effect of the current contrast limitations of non-coronagraphic, low Strehl, Hα imaging with older AO systems. We predict that, as higher Strehl AO systems (with high-performance custom coronagraphs; like MagAO-X) are utilized at Hα, the number of detected gap planets will substantially increase by, as much as, tenfold.

When the real first light contrasts of MagAO-X are applied to the MAG model, direct detections of a large number (~21-42) of new accreting protoplanets is predicted. Such a large number of newly discovered protoplanets will significantly improve our understanding of planet formation, solar system architectures, and planet disk interactions.

ACKNOWLEDGMENTS

We thank Logan Francis and Nienke van der Marel for permission to reproduce their ALMA images in Fig 5. We would also like to thank Sebastiaan Haffert (for the background for Fig 6). Laird Close was supported by a NASA eXoplanet Research Program (XRP) grant 80NSSC18K0441. The research of DD and FS leading to these results has received funding from the European Research Council under ERC Starting Grant agreement 678194 FALCONER). We are very grateful for support from the NSF MRI Award #1625441 (MagAO-X).

REFERENCES

[1] Close, L.M. *The Separation and Hα Contrasts of Massive Accreting Planets in the Gaps of Transitional Disks: Predicted Hα Protoplanet Yields for Adaptive Optics Surveys* (2020) The Astronomical Journal, Volume 160, Issue 5, id.221, 16 pp.

[2] Francis, Logan; van der Marel, Nienke (FVDM), *Dust-depleted Inner Disks in a Large Sample of Transition Disks through Long-baseline ALMA Observations*, The Astrophysical Journal, Volume 892, Issue 2, id.111, 2020

[3] Greenbaum, Alexandra Z.; Pueyo, Laurent; Sivaramakrishnan, Anand; Lacour, Sylvestre, "*An Image-plane Algorithm for JWST's Non-redundant Aperture Mask Data*", 2015, ApJ 798, 68

[4] Nielsen, Eric L.; De Rosa, Robert J.; Macintosh, Bruce; Wang, Jason J.; Ruffio, Jean-Baptiste; Chiang, Eugene; Marley, Mark S.; Saumon, Didier; Savransky, Dmitry; Ammons, S. Mark; Bailey, Vanessa P.; Barman, Travis; Blain, Célia; Bulger, Joanna; Burrows, Adam; Chilcote, Jeffrey; Cotten, Tara; Czekala, Ian; Doyon, Rene; Duchêne, Gaspard Esposito, Thomas M.; Fabrycky, Daniel; Fitzgerald, Michael P.; Follette, Katherine B.; Fortney, Jonathan J.; Gerard, Benjamin L.; Goodsell, Stephen J.; Graham, James R.; Greenbaum, Alexandra Z.; Hibon, Pascale; Hinkley, Sasha; Hirsch, Lea A.; Hom, Justin; Hung, Li-Wei; Dawson, Rebekah Ilene; Ingraham, Patrick; Kalas, Paul; Konopacky, Quinn; Larkin, James E.; Lee, Eve J.; Lin, Jonathan W.; Maire, Jérôme; Marchis, Franck; Marois, Christian; Metchev, Stanimir; Millar-Blanchaer, Maxwell A.; Morzinski, Katie M.; Oppenheimer, Rebecca; Palmer, David; Patience, Jennifer; Perrin, Marshall; Poyneer, Lisa; Pueyo, Laurent; Rafikov, Roman R.; Rajan, Abhijith; Rameau, Julien; Rantakyrö, Fredrik T.; Ren, Bin; Schneider, Adam C.; Sivaramakrishnan, Anand; Song, Inseok; Soummer, Remi; Tallis, Melisa;

Thomas, Sandrine; Ward-Duong, Kimberly; Wolff, Schuyler, *The Gemini Planet Imager Exoplanet Survey: Giant Planet and Brown Dwarf Demographics from 10 to 100 au*, The Astronomical Journal, Volume 158, Issue 1, article id. 13, 44 pp. (2019).

[5] Close L.M. Follette, K. B.; Males, J. R.; Puglisi, A.; Xompero, M.; Apai, D.; Najita, J.; Weinberger, A. J.; Morzinski, K.; Rodigas, T. J.; Hinz, P.; Bailey, V.; Briguglio, R. *Discovery of Hα Emission from the Close Companion inside the Gap of Transitional Disk HD 142527* 2014, ApJ Lett 781 L30

[6] Sallum, S., Follette, K. Eisner, J., Close, L.M. Hinz, P.; Kratter, K.; Males, J.; Skemer, A.; Macintosh, B.; Tuthill, P.; Bailey, V.; Defrère, D.; Morzinski, K.; Rodigas, T.; Spalding, E.; Vaz, A.; Weinberger, A. J. "*Accreting Protoplanets in the LkCa 15 Transition Disc*" Nov 19, 2015 issue of Nature, L1. https://arxiv.org/abs/1511.07456

[7] Wagner, Kevin; Follete, Katherine B.; Close, Laird M.; Apai, Dániel; Gibbs, Aidan; Keppler, Miriam; Müller, André; Henning, Thomas; Kasper, Markus; Wu, Ya-Lin; Long, Joseph; Males, Jared; Morzinski, Katie; McClure, Melissa, *Magellan Adaptive Optics Imaging of PDS 70: Measuring the Mass Accretion Rate of a Young Giant Planet within a Gapped Disk* The Astrophysical Journal Letters, Volume 863, Issue 1, article id. L8, 6 pp. (2018).

[8] Haffert, S. Y.; Bohn, A. J.; de Boer, J.; Snellen, I. A. G.; Brinchmann, J.; Girard, J. H.; Keller, C. U.; Bacon, R. *Two accreting protoplanets around the young star PDS 70*, Nature Astronomy, Volume 3, p. 749-754, 2019

[9] Males, Jared R.; Close, Laird M.; Miller, Kelsey; Schatz, Lauren; Doelman, David; Lumbres, Jennifer; Snik, Frans; Rodack, Alex; Knight, Justin; Van Gorkom, Kyle; Long, Joseph D.; Hedglen, Alex; Kautz, Maggie; Jovanovic, Nemanja; Morzinski, Katie; Guyon, Olivier; Douglas, Ewan; Follette, Katherine B.; Lozi, Julien; Bohlman, Chris Durney, Olivier; Gasho, Victor; Hinz, Phil; Ireland, Michael; Jean, Madison; Keller, Christoph; Kenworthy, Matt; Mazin, Ben; Noenickx, Jamison; Alfred, Dan; Perez, Kevin; Sanchez, Anna; Sauve, Corwynn; Weinberger, Alycia; Conrad, Al, *MagAO-X: project status and first laboratory results*, Proceedings of the SPIE, Volume 10703, id. 1070309 14 pp. (2018).

[10] Close, L.M; Males, Jared R.; Durney, Olivier; Sauve, Corwynn; Kautz, Maggie; Hedglen, Alex; Schatz, Lauren; Lumbres, Jennifer; Miller, Kelsey; Van Gorkom, Kyle; Jean, Madison; Gasho, Victor, *Optical and mechanical design of the extreme AO coronagraphic instrument MagAO-X*, Proceedings of the SPIE, Volume 10703, id. 107034Y 10 pp. (2018). https://arxiv.org/ftp/arxiv/papers/1807/1807.04311.pdf

[11] Males, Jared R. Close, Laird M., et al. *MagAO-X First Light* Proc. SPIE 11448, # 218 (2020) *these proceedings.*

[12] Marois, C., Nadeau, D., Doyon, R., Racine, R., & Walker, G. A. H. 2003, in IAU Symposium, 275

[13] Close, L.M. Lenzen, Rainer; Guirado, Jose C.; Nielsen, Eric L.; Mamajek, Eric E.; Brandner, Wolfgang; Hartung, Markus; Lidman, Chris; Biller, Beth *A dynamical calibration of the mass-luminosity relation at very low stellar masses and young ages* 2005 Nature 433, 286.

[14] Otten, Gilles P. P. L.; Snik, Frans; Kenworthy, Matthew A.; Keller, Christoph U.; Males, Jared R.; Morzinski, Katie M.; Close, Laird M.; Codona, Johanan L.; Hinz, Philip M.; Hornburg, Kathryn J *"On-sky Performance Analysis of the Vector Apodizing Phase Plate Coronagraph on MagAO/Clio2*" 2017, ApJ 834, 175

[15] Hashimoto, Jun; Aoyama, Yuhiko; Konishi, Mihoko; Uyama, Taichi; Takasao, Shinsuke; Ikoma, Masahiro; Tanigawa, Takayuki, Accretion Properties of PDS 70b with MUSE, The Astronomical Journal, Volume 159, Issue 5, id.222, 2020

[16] Keppler, M.; Benisty, M.; Müller, A.; Henning, Th.; van Boekel, R.; Cantalloube, F.; Ginski, C.; van Holstein, R. G.; Maire, A. -L.; Pohl, A.; Samland, M.; Avenhaus, H.; Baudino, J. - L.; Boccaletti, A.; de Boer, J.; Bonnefoy, M.; Chauvin, G.; Desidera, S.; Langlois, M.;

Lazzoni, C. Marleau, G. -D.; Mordasini, C.; Pawellek, N.; Stolker, T.; Vigan, A.; Zurlo, A.; Birnstiel, T.; Brandner, W.; Feldt, M.; Flock, M.; Girard, J.; Gratton, R.; Hagelberg, J.; Isella, A.; Janson, M.; Juhasz, A.; Kemmer, J.; Kral, Q.; Lagrange, A. -M.; Launhardt, R.; Matter, A.; Ménard, F.; Milli, J.; Mollière, P.; Olofsson, J.; Pérez, L.; Pinilla, P.; Pinte, C.; Quanz, S. P.; Schmidt, T.; Udry, S.; Wahhaj, Z.; Williams, J. P.; Buenzli, E.; Cudel, M.; Dominik, C.; Galicher, R.; Kasper, M.; Lannier, J.; Mesa, D.; Mouillet, D.; Peretti, S.; Perrot, C.; Salter, G.; Sissa, E.; Wildi, F.; Abe, L.; Antichi, J.; Augereau, J. -C.; Baruffolo, A.; Baudoz, P.; Bazzon, A.; Beuzit, J. -L.; Blanchard, P.; Brems, S. S.; Buey, T.; De Caprio, V.; Carbillet, M.; Carle, M.; Cascone, E.; Cheetham, A.; Claudi, R.; Costille, A.; Delboulbé, A.; Dohlen, K.; Fantinel, D.; Feautrier, P.; Fusco, T.; Giro, E.; Gluck, L.; Gry, C.; Hubin, N.; Hugot, E.; Jaquet, M.; Le Mignant, D.; Llored, M.; Madec, F.; Magnard, Y.; Martinez, P.; Maurel, D.; Meyer, M.; Möller-Nilsson, O.; Moulin, T.; Mugnier, L.; Origné, A.; Pavlov, A.; Perret, D.; Petit, C.; Pragt, J.; Puget, P.; Rabou, P.; Ramos, J.; Rigal, F.; Rochat, S.; Roelfsema, R.; Rousset, G.; Roux, A.; Salasnich, B.; Sauvage, J. -F.; Sevin, A.; Soenke, C.; Stadler, E.; Suarez, M.; Turatto, M.; Weber, L. *Discovery of a planetary-mass companion within the gap of the transition disk around PDS 70*, Astronomy & Astrophysics, Volume 617, id.A44, 21 pp. 2018

[17] Wang, Jason J.; Ginzburg, Sivan; Ren, Bin; Wallack, Nicole; Gao, Peter; Mawet, Dimitri; Bond, Charlotte Z.; Cetre, Sylvain; Wizinowich, Peter; De Rosa, Robert J.; Ruane, Garreth; Liu, Michael C.; Absil, Olivier; Alvarez, Carlos; Baranec, Christoph; Choquet, Élodie; Chun, Mark; Defrère, Denis; Delorme, Jacques-Robert; Duchêne, Gaspard Forsberg, Pontus; Ghez, Andrea; Guyon, Olivier; Hall, Donald N. B.; Huby, Elsa; Jolivet, Aïssa; Jensen-Clem, Rebecca; Jovanovic, Nemanja; Karlsson, Mikael; Lilley, Scott; Matthews, Keith; Ménard, François; Meshkat, Tiffany; Millar-Blanchaer, Maxwell; Ngo, Henry; de Xivry, Gilles Orban; Pinte, Christophe; Ragland, Sam; Serabyn, Eugene; Catalán, Ernesto Vargas; Wang, Ji; Wetherell, Ed; Williams, Jonathan P.; Ygouf, Marie; Zuckerman, Ben *Keck/NIRC2 L'-band Imaging of Jovian-mass Accreting Protoplanets around PDS 70*, The Astronomical Journal, Volume 159, Issue 6, id.263, 2020

[18] Alexander, Richard D.; Armitage, Philip J. 2009 Astrophysical Journal, Volume 704, Issue 2, pp. 989-1001

[19] Dodson-Robinson S, & Salyk C.*(DRS) "Transitional Disks as Signposts of Young, Multiplanet Systems"* 2011 ApJ, 738, 131 http://adsabs.harvard.edu/abs/2011ApJ...738..131D

[20] Owen, James E., The Origin and Evolution of Transition Discs: Successes, Problems, and Open Questions, Publications of the Astronomical Society of Australia, Volume 33, id.e005 22 pp. 2016

[21] Brittain, Sean D.; Najita, Joan R.; Dong, Ruobing; Zhu, Zhaohuan, The Planetary Luminosity Problem: "Missing Planets" and the Observational Consequences of Episodic Accretion, eprint arXiv:2003.11980, March 2020

[22] Marois, Christian; Zuckerman, B.; Konopacky, Quinn M.; Macintosh, Bruce; Barman, Travis, *Images of a fourth planet orbiting HR 8799*, Nature, Volume 468, Issue 7327, pp. 1080-1083 (2010).

[23] Currie, Thayne; Burrows, Adam; Itoh, Yoichi; Matsumura, Soko; Fukagawa, Misato; Apai, Daniel; Madhusudhan, Nikku; Hinz, Philip M.; Rodigas, T. J.; Kasper, Markus; Pyo, T. -S.; Ogino, Satoshi, *A Combined Subaru/VLT/MMT 1-5 μm Study of Planets Orbiting HR 8799: Implications for Atmospheric Properties, Masses, and Formation*, The Astrophysical Journal, Volume 729, Issue 2, article id. 128, 20 pp. (2011).

[24] Dong, Ruobing; Fung, Jeffrey, *What is the Mass of a Gap-opening Planet?,* The Astrophysical Journal, Volume 835, Issue 2, article id. 146, 16 pp. (2017).

[25] Goździewski, Krzysztof; Migaszewski, Cezary, *Multiple mean motion resonances in the HR 8799 planetary system*, Monthly Notices of the Royal Astronomical Society, Volume 440, Issue 4, p.3140-3171, 2014

[26] Papaloizou, John C. B.; Terquem, Caroline, *Planet formation and migration,* Reports on Progress in Physics, Volume 69, Issue 1, pp. 119-180 (2006).

[27] Thanathibodee, Thanawuth; Calvet, Nuria; Bae, Jaehan; Muzerolle, James; Hernández, Ramiro Franco *Magnetospheric Accretion as a Source of Hα Emission from Protoplanets around PDS 70*, The Astrophysical Journal, Volume 885, Issue 1, article id. 94, 8 pp. (2019).

[28] Szulagyi J. and Ercolano, B. *Hydrogen recombination line luminosities and -variability from forming planets*, preprint arXiv:2002.09918v1

[29] Close, L.M. Roddier, F.; Hora, J. L.; Graves, J. E.; Northcott, M.; Roddier, C.; Hoffman, W. F.; Dayal, A.; Fazio, G. G.; Deutsch, L. K. *Adaptive Optics Infrared Imaging Polarimetry and Optical HST Imaging of Hubble's Variable Nebula (R Monocerotis/NGC 2261): A Close Look at a Very Young Active Herbig Ae/Be Star* 1997 ApJ 489 210

[30] Males, Jared R.; Close, Laird M.; Morzinski, Katie M.; Wahhaj, Zahed; Liu, Michael C.; Skemer, Andrew J.; Kopon, Derek; Follette, Katherine B.; Puglisi, Alfio; Esposito, Simone; Riccardi, Armando; Pinna, Enrico; Xompero, Marco; Briguglio, Runa; Biller, Beth A.; Nielsen, Eric L.; Hinz, Philip M.; Rodigas, Timothy J.; Hayward, Thomas L.; Chun, Mark; Ftaclas, Christ; Toomey, Douglas W.; Wu, Ya-Lin *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* 2014a ApJ 786, 32.

[31] Rigliaco, 2012, A&A 548, A56

[32] Gullbring, Erik; Hartmann, Lee; Briceno, Cesar; Calvet, Nuria 1998, ApJ 492, 323

[33] Lubow 1999 ApJ 526, 1001

[34] Currie, Thayne; Marois, Christian; Cieza, Lucas; Mulders, Gijs D.; Lawson, Kellen; Caceres, Claudio; Rodriguez-Ruiz, Dary; Wisniewski, John; Guyon, Olivier; Brandt, Timothy D.; Kasdin, N. Jeremy; Groff, Tyler D.; Lozi, Julien; Chilcote, Jeffrey; Hodapp, Klaus; Jovanovic, Nemanja; Martinache, Frantz; Skaf, Nour; Lyra, Wladimir; Tamura, Motohide Asensio-Torres, Ruben; Dong, Ruobing; Grady, Carol; Gerard, Benjamin; Fukagawa, Misato; Hand, Derek; Hayashi, Masahiko; Henning, Thomas; Kudo, Tomoyuki; Kuzuhara, Masayuki; Kwon, Jungmi; McElwain, Michael W.; Uyama, Taichi *No Clear, Direct Evidence for Multiple Protoplanets Orbiting LkCa 15: LkCa 15 bcd are Likely Inner Disk Signals*, The Astrophysical Journal Letters, Volume 877, Issue 1, article id. L3, 8 pp. (2019).

[35] Keppler, M.; Teague, R.; Bae, J.; Benisty, M.; Henning, T.; van Boekel, R.; Chapillon, E.; Pinilla, P.; Williams, J. P.; Bertrang, G. H. -M.; Facchini, S.; Flock, M.; Ginski, Ch.; Juhasz, A.; Klahr, H.; Liu, Y.; Müller, A.; Pérez, L. M.; Pohl, A.; Rosotti, G. Samland, M.; Semenov, D., *Highly structured disk around the planet host PDS 70 revealed by high-angular resolution observations with ALMA*, Astronomy & Astrophysics, Volume 625, id.A118, 15 pp. 2019

[36] Pérez, Laura M.; Isella, Andrea; Carpenter, John M.; Chandler, Claire J., *Large-scale Asymmetries in the Transitional Disks of SAO 206462 and SR 21*, The Astrophysical Journal Letters, Volume 783, Issue 1, article id. L13, 6 pp. (2014).

[37] Thomas-Osip, J. E.; Lederer, S. M.; Osip, D. J.; Vilas, F.; Domingue, D.; Jarvis, K.; Leed s, S. L. 2008 proc SPIE Volume 7012, article id. 70121U

[38] Cugno, G, Cugno, G.; Quanz, S. P.; Hunziker, S. et al. 2019, A&A 622, 156

[39] Zurlo, A.; Cugno, G.; Montesinos, M.; Perez, S.; Canovas, H.; Casassus, S.; Christiaens, V.; Cieza, L.; Huelamo, N., *The widest Hα survey of accreting protoplanets around nearby transition disks*, Astronomy & Astrophysics, Volume 633, id.A119, 9 pp. 2020