An extended scattered light disk around AT Pyx

Possible planet formation in a cometary globule

C. Ginski\textsuperscript{1,2}, R. Gratton\textsuperscript{3}, A. Bohn\textsuperscript{2}, C. Dominek\textsuperscript{1}, S. Jorquera\textsuperscript{5}, G. Chauvin\textsuperscript{4,5}, J. Milli\textsuperscript{4}, M. Rodriguez\textsuperscript{6,1,5}, M. Benisty\textsuperscript{4,5}, R. Launhardt\textsuperscript{7}, A. Müller\textsuperscript{7}, G. Cugno\textsuperscript{8}, R. G. van Holstein\textsuperscript{2}, A. Boccaletti\textsuperscript{9}, G. A. Muro-Arena\textsuperscript{1}, S. Desidera\textsuperscript{3}, M. Keppler\textsuperscript{7}, A. Zurlo\textsuperscript{10}, E. Sissa\textsuperscript{3}, T. Henning\textsuperscript{7}, M. Janson\textsuperscript{7,11}, M. Langlois\textsuperscript{12,13}, M. Bonnefoy\textsuperscript{4}, F. Cantalloube\textsuperscript{7}, V. D’Orazi\textsuperscript{3}, M. Feldt\textsuperscript{4}, J. Hagelberg\textsuperscript{14}, D. Ségransan\textsuperscript{14}, A-M. Lagrange\textsuperscript{4}, C. Lazzoni\textsuperscript{3}, M. Meyer\textsuperscript{15}, C. Romero\textsuperscript{4}, T. O. B. Schmidt\textsuperscript{3,16}, A. Vigan\textsuperscript{13}, C. Petit\textsuperscript{17}, R. Roelfsema\textsuperscript{18}, J. Pragt\textsuperscript{18}, and L. Weber\textsuperscript{14}

(Affiliations can be found after the references)

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ABSTRACT

Aims. To understand how the multitude of planetary systems that have been discovered come to be, we need to study systems at different evolutionary stages, with different central stars but also in different environments. The most challenging environment for planet formation may be the harsh UV radiation field of nearby massive stars which quickly erodes disks by external photo-evaporation. We observed the ATPyx system, located in the head of a cometary globule in the Gum Nebula, to search for signs of ongoing planet formation.

Methods. We used the extreme adaptive optics imager VLT/SPHERE in Dual Beam Polarization Imaging Mode in \textit{H}-band as well as in IRDIS Extended mode (K12-band imaging and Y-H integral field spectroscopy) to observe AT Pyx in polarized light and total intensity. Additionally, we employed VLT/NACO to observe the system in the \textit{L}-band.

Results. We resolve the disk around AT Pyx for the first time in scattered light across multiple wavelengths in polarized light and total intensity. We find an extended (≥126 au) disk, with an intermediate inclination of between 35\textdegree and 42\textdegree. The disk shows a complex substructure and we identify two or possibly three spiral-like features. Depending on the precise geometry of the disk (which we cannot unambiguously infer from our data), the disk may be eccentric with an eccentricity of ~0.16 or partially self-shadowed. The spiral features and possible eccentricity are both consistent with signatures of an embedded gas giant planet with a mass of ~1\textit{M}\textsubscript{Jup}. Our own observations can rule out brown dwarf companions embedded in the resolved disk, but are nevertheless not sensitive enough to confirm or rule out the presence of a gas giant.

Conclusions. AT Pyx is the first disk to be spatially resolved in a cometary globule in the Gum Nebula. By comparison with disks in the Orion Nebula Cluster we note that the extension of the disk may be exceptional for this environment if the external UV radiation field is indeed comparable to other cometary globules in the region. The signposts of ongoing planet formation are intriguing and need to be followed up with either higher sensitivity or at different wavelengths.

Key words. planets and satellites: formation – protoplanetary disks – instrumentation: adaptive optics – techniques: polarimetric – high angular resolution

1. Introduction

AT Pyx (= IRAS 08267-3336, WRAY 15-220) is a young intermediate-mass star located in the Gum Nebula (Herczeg & Hillenbrand 2014), a large H\textsc{ii} region in the southern hemisphere. Its distance was recently revised by \textit{Gaia} to be 370 ± 5 pc (Gaia Collaboration 2021; Lindegren et al. 2021). Using the luminosity and temperature derived by Herczeg & Hillenbrand (2014) and re-scaled to the new \textit{Gaia} distance in combination with Siess et al. (2000) stellar isochrone models, we find a stellar mass of 1.5 ± 0.1\textit{M}\textsubscript{\odot} and an age of 5.1\textsuperscript{±1.0} Myr.

AT Pyx was first identified as a pre-main sequence star by Pettersson (1987), who measured significant \textit{H}\textalpha emission. We show the spectral energy distribution (SED) of the system in Fig. 1, assembled from various photometric catalogues. We note that Herczeg & Hillenbrand (2014) measured an extinction of \textit{A}_\text{V} = 1.2 mag toward the system. A clear infrared (IR) excess is present at wavelengths longer than 10 μm. The dip in emission at the same wavelength is typical for a transition disk with an inner cavity. Garufi et al. (2018) find a fractional near-infrared (NIR) excess of \textit{F}_{\text{NIR}}/\textit{F}_\text{\textit{V}} = 20.5 \pm 2.3\% and a far-infrared (FIR) excess of \textit{F}_{\text{FIR}}/\textit{F}_\text{\textit{V}} = 39.8 \pm 3.2\%. The large FIR excess is comparable to that of well-known extended disks such as the ones around HD142527 (Rodigas et al. 2014; Avenhaus et al. 2014) or GG Tau (McCabe et al. 2002; Itoh et al. 2014; Kepller et al. 2020). The lower NIR excess, compared to the FIR excess, is typical for disks bright in scattered light (Garufi et al. 2018).

In the All-Sky Automated Survey for SuperNovae (ASAS-SN) catalog (Jayasinghe et al. 2019), a strong V-band variability of AT Pyx was found with an amplitude of 1.45 mag and timescales on the order of days. This may indicate that AT Pyx is a so-called “dipper” star in which inner disk material is obscuring the star periodically (see e.g., Stauffer et al. 2015; McGinnis et al. 2015).
2. Observations and data reduction

In the following we describe our observation setup and the data reduction of all observing epochs.

2.1. SPHERE observations

2.1.1. Polarimetric observations

AT Pyx was observed on May 15, 2017, with SPHERE/IRDIS (Dohlen et al. 2008) in dual polarization imaging mode (DPI; Langlois et al. 2014; de Boer et al. 2020; van Holstein et al. 2020). Observations were carried out in $H$-band with a coronagraph blocking the central region of the system (92.5 mas inner working angle, Cariblet et al. 2011) and the instrument de-rotator operating in field-stabilized mode. The observations were part of the SPHERE guaranteed time survey of nearby T Tauri stars. We give the detailed observation setup and conditions in Table 1.

The data reduction was performed with the IRDIS pipeline for Accurate Polarimetry (IRDAP, van Holstein et al. 2020) using default parameters. The details of the data reduction are described in van Holstein et al. (2020). We show the final $Q_\phi$ image in the bottom-right panel of Fig. 2. The $Q_\phi$ image contains all the azimuthally polarized signal as positive values and all radial polarized signal as negative values; see de Boer et al. (2020) and Monnier et al. (2019) for a detailed explanation. For a single star illuminating a nearly face-on circumstellar disk we expect in principle only azimuthally polarized light and thus the $Q_\phi$ image should give the majority of the scattered light signal received from the system. We additionally show the initial combined and flux calibrated Stokes $Q$ and $U$ images as well as the complementary $U_0$ image in Appendix A.

2.1.2. Intensity observations

We observed AT Pyx in SPHERE IRDIFS mode on April 18, 2018, within the SPHERE Consortium Guaranteed Time Observations. The IRDIFS-EXT mode uses – simultaneously – the Integral Field Spectrograph (IFS: Claudi et al. 2008) over the wavelength range 0.95–1.65 $\mu$m at a spectral resolution of $R \sim 30$ (field of view 1.77 arcsec square) and the dual band imager IRDIS (Dohlen et al. 2008) for the $K_1$ and $K_2$ narrow bands at 2.09 and 2.22 $\mu$m, respectively, over a wider field of view of $\sim$10 arcsec square. We used the ALC_Ks coronograph (Boccaletti et al. 2008) with a field mask of 120 mas in radius. Observing conditions were excellent with a median DIMM seeing of 0.5 arcsec with respect the coronagraph for flux and point spread function calibration, observations with a bi-dimensional sinusoidal pattern imprinted on the deformable mirror to provide faint replicas of the stellar image for fine centering (Beuzit et al. 2019) and background sky observations.

Data were reduced using the SPHERE DRH pipeline (Pavlov et al. 2008) and additional routines available at the SPHERE Data Center (Delorme et al. 2017). The data were then analyzed using the SPECAL routines (Galicher et al. 2018), which includes simple rotation and sum, angular differential imaging (ADI: Marois et al. 2006), TLOCI (Marois et al. 2014); and principal component analysis (PCA: Soummer et al. 2012; Amara & Quanz 2012). For IFS, we also used additional routines based on the PCA method simultaneously in space and wavelength coordinates developed at INAF – Osservatorio Astronomico di Padova (Mesa et al. 2015).

The system is located in the head of a cometary globule (see Fig. 2, left), which is a dense region of molecular gas with a fading tail (Hawarden & Brand 1976). The origin of the cometary globules are still not entirely clear. They may have been formed from a collapsing cloud that went supernova roughly 1.5 Myr ago (Sahau et al. 1988), or they may be caused by the interaction with the high-intensity field of the Vela OB association (Choudhury & Bhatt 2009). Cometary globules have been found to be sites of enhanced star formation, likely triggered by the same event that created the Gum Nebula (Bhatt 1993).

Due to the UV environment caused by the nearby Vela OB association, it is thought that circumstellar disks should have a shortened lifetime compared to low-mass star forming regions. Indeed, Kim et al. (2005) found that out of the 11 PMS stars located in cometary globules that they observed, only 1 showed a significant IR excess. This led them to the conclusion that the typical disk lifetime should be shorter than 5 Myr due to external photo-evaporation. However, the cometary globules observed by Kim et al. (2005) are located closer to the O4 star $\zeta$ Pup than the cometary globule that hosts AT Pyx, and therefore the UV background radiation should be lower in the case of AT Pyx.

Güdel et al. (2010) detected ionized Neon in the mid-infrared (MIR) towards AT Pyx, indicative of stellar X-ray or extreme ultraviolet (EUV) radiation hitting the surface of a circumstellar disk. This may be an indication of an enhanced EUV external radiation field, but might also be explained by the chromospheric activity of AT Pyx itself.

In this study we present high-resolution scattered light observations of the AT Pyx system in the NIR with VLT/SPHERE (Beuzit et al. 2019) and VLT/NACO (Lenzen et al. 2003; Rousset et al. 2003).
Fig. 2. Left: dark Energy Cam Plane Survey (DECaPS, Schlafly et al. 2018) optical multi-band image of the head of the cometary globule CG-22 in the Gum Nebula. The red dashed lines indicate the position of AT Pyx. Right from top to bottom: NACO L-band ADI image of the disk around AT Pyx; SPHERE K-band ADI image and SPHERE H-band polarized light image.

Table 1. Observation setup and observing conditions.

<table>
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<th>Filter</th>
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<th>DIT [s]</th>
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<th>Seeing [arcsec]</th>
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<td>13 800</td>
<td>0.80</td>
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</table>

2.2. NACO observations

The NACO observations were obtained on January 19, 2019, as part of the ISPY (Imaging Survey for Planets around Young stars, Launhardt et al. 2020) observation campaign. Observations were carried out in the L' filter with the L27 objective and a pixel scale of 27.19 mas. As AT Pyx is relatively faint in the L-band, no coronagraph was used to block the central star. To accurately sample the variable sky background in the L-band the individual frame exposure time was set to 0.2 s. The total integration was 46 min. The observation setup and conditions are summarized in Table 1.

The data were reduced using the IPAG-ADI pipeline (Chauvin et al. 2012). Data calibration (flat-fielding, bad pixels, and sky removal) was performed as a first step on all available cubes. To reduce computation time, subframes of 90 × 90 pixels (FoV of 2.4'' × 2.4'') were extracted. Finally, these frames were re-centered and bad frames (poorly saturated, overly extended PSF) were removed to obtain a final master cube used for the data reduction.

The pipeline allows for the use of multiple flavors of ADI algorithms, namely classical ADI (cADI), smart ADI (sADI), radial ADI (rADI), all described in Chauvin et al. (2012), as well as Locally Optimized Combination of Images (LOCI, Lafrënière et al. 2007) and Principal Component Analysis (PCA, Soummer et al. 2012). The use of multiple ADI techniques, together with the LOCI and PCA reduction, allows for comparison and consistency on the results obtained. For sADI and LOCI, we followed a similar configuration as Chauvin et al. (2012), with a FWHM = 4.5 pixels and a separation criteria of 0.75 × FWHM at the companion separation. For the PCA method (e.g., Soummer et al. 2012), observations were reduced using three different numbers of modes (k = 1, 5, 20) and masking the image outside of a radius of 60 pixels.
Given our data, we propose two scenarios for the disk inclination and $B$.2. 

The interpretation of the observed structures depends strongly on the projection effects due to the disk inclination. Given our data, we propose two scenarios for the disk inclination and position angle which we also illustrate in Fig. 4:

**Disk position angle of $\sim 90^\circ$.** The features A1 and A2 could represent the ansae of an inclined disk. They appear particularly bright in polarized light, which could be an effect of the polarized phase function peaking at scattering angles of $\sim 90^\circ$. If this is the case, then we would expect the near side of the disk to be in the north, because in all data sets we receive more flux from the north compared to the south, consistent with smaller scattering angles. If this interpretation is correct then we should be able to fit features A1 and A2 with a single ellipse (assuming that both features trace the same height structure in scattered light). As is visible in Fig. 3, the curvature of feature A1 appears to be larger than of feature A2, which is inconsistent with this picture. However, it may be that we misidentified feature S1 as an individual spiral-like feature and that instead it is a continuation of feature A2. In this case the discontinuity between the eastern tip of S1 and the northern tip of A1, which is highlighted in the central panel of Fig. 3, is puzzling. Such a discontinuity might be explained if a shadow is cast on the outer ring from an inner (unresolved) disk with a relative inclination, similar to the case of the HD 142527 system (see e.g., Marino et al. 2015). The corresponding shadow in the south might then not be detected due to the general low signal in that region. It might also be possible that feature S1 is a spiral arm that is significantly lifted above the disk surface profile. In this case, the discontinuity might simply be a projection effect. A combination of both explanations for the appearance of the northern side of the disk is also possible, that is, a spiral arm with a significantly increased scale height compared to the surrounding disk, which casts shadows on the surrounding structures.

If we fit features A1 and A2 (ignoring feature S1) with an ellipse, then we find an inclination of the disk of $\sim 42^\circ$ and a semi-major axis of the outer features of $\sim 126au$. However, to allow for a simultaneous fit of both features with the same ellipse, the center needs to be offset from the central star by 55 mas. Such an offset along the major axis cannot be explained by projection effects and would indicate that the disk is eccentric with an eccentricity of $\sim 0.16$.

**Disk position angle of $\sim 0^\circ$.** In order to allow for a non-eccentric outer ring traced by features A1 and A2, we consider.

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1 We investigate why the ring-like features do not appear in the IFS data in Appendix C.
that the disk position angle might rather be close to \(\sim 0^\circ\). In this scenario, it is possible to fit both features with an ellipse with an offset along the minor axis of the disk. This offset can be explained by the projection of a flared and inclined disk with the near side in the west (see e.g., de Boer et al. 2016). Feature A2 appears brighter than A1 in the SPHERE \(H\)-band and the \(K\)-band images\(^2\). This may then be explained by the scattering phase function, if A2 is the near side and thus is seen under smaller angles. This is consistent with feature A2 being closer to the stellar position in the 2D plane than feature A1. Assuming this position angle, we find a similar inclination of the disk to the previous scenario of \(\sim 35^\circ\) with a semi-major axis of the outer features of \(\sim 145\) au. However, we caution that in this scenario the ansae of the disk are not seen, and so the semi-major axis and the inclination are less constrained.

If we assume this orientation, then the lack of flux in the south and southwest in the polarized light data is puzzling, because these areas would be seen under close to \(90^\circ\) scattering angles and the degree of polarization should be near maximum compared to any other area in the disk. Thus, if this is the correct disk orientation we require that the south and southwest but also the north and northeast are shadowed by interior structures. In the north this may be due to the spiral-like features S1 and S2. While S3 seemingly extends into the south in the left panel of Fig. 3, it does not extend visibly to the southwest, where we would expect the peak of the polarized scattered light signal. However, the polarized light \(H\)-band data show signal close to the coronagraph in the north and south, which is most visible in the right panel of Fig. 3. If this signal traces an inner disk that is misaligned with respect to the outer disk, traced by features A1 and A2, then this may produce the required shadowing along the ansae.

Based on our data sets, we are unable to unambiguously determine which of the proposed scenarios represents the correct interpretation of the disk morphology. Longer wavelength data, such as millimeter continuum or line emission observations, are needed to disentangle the large- and small-scale morphology of the disk. We do note however that the strong optical variability of AT Pyx might favor a rather inclined inner disk, consistent with the shadowing scenario and a disk position angle of \(0^\circ\).

### 4. Planet detection limits

The spiral features discussed in the previous section might be an indication of a perturber embedded in the disk, such as a forming planet or a low-mass stellar component. Both of these latter objects would be expected to be brightest relative to the central star at long wavelengths. Additionally, the optical depth of the disk decreases towards longer wavelengths allowing us to observe more embedded objects.

In neither the SPHERE \(K\)-band data nor the NACO \(L\)-band data do we find unambiguous signatures of a point source in or directly outside the disk. We note that due to the complex substructure in combination with the ADI processing, it is possible to produce false-positive or false-negative results (see e.g., the case of LkCa 15, Currie et al. 2019). In Fig. 2, there is a tantalizing point-like feature present in the NACO data at a separation of roughly \(0.1^\prime\) to the southwest of the star. However, this signal has no counterpart in the higher contrast SPHERE \(K\)-band or the SPHERE IFS data. We therefore assume it is an ADI-distorted disk structure or a remnant of the stellar PSF.

Using the SPHERE and NACO data, we computed contrast limits, which are shown in Fig. 5. To transform these contrast limits into mass detection limits, we used AMES-DUSTY models (Allard et al. 2012), with a system age of 5 Myr. To compute absolute magnitudes from the contrast limits we utilized the 2MASS \(K\)-band magnitude of the system of 9.044 \(\pm\) 0.03 mag. In Fig. 5, we achieve significantly lower contrast due to the coinciding disk structures. We can firmly rule out brown dwarf or low-mass stellar companions, but are not sensitive to massive gas giant planets.

We note that the presented detection limits do not take into account extinction effects. Given that the system is still young, it is conceivable that planets inside the disk cavity are (partially) enshrouded by circumplanetary material. This may to a lesser degree also be the case for planets outside of the disk. Extinction may lead to shallower detection limits than shown in Fig. 2. For a recent, detailed discussion of these effects we refer to Asensio-Torres et al. (2021).

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\(^2\) We note that in principle only the SPHERE \(H\)-band image preserves the (polarized light) photometry, while this is not the case for the ADI processed \(K\) and \(L\)-band images which suffer from possibly complex self-subtraction effects.
find configurations with three spiral arms that are similar in appearance to the observations of AT Pyx. This typically requires planets at least more massive than Neptune (Dong & Fung 2017).

In scenario 1, which we outlined for the disk geometry, with a position angle of ~90°, we find that the disk must be eccentric. Such an eccentricity may also be well explained by an embedded massive planet. Zhang et al. (2018) ran an extensive grid of hydrodynamic models and found that for their higher mass planets (>1 \( M_{\text{Jup}} \)) and small disk aspect ratios at the planet position of h/r = 0.50 to 0.07, the planet opens a significantly eccentric gap in the gas (e > 0.15). As we trace micron-sized particles that are well coupled to the gas we can expect to trace such an eccentricity also in scattered light (Muro-Arena et al., in prep.). To estimate whether or not such a high planet mass may be consistent with our observations we used the relation between planet mass, spiral scattered light peak contrast, and aspect ratio found by Dong & Fung (2017). As feature S2 is the most unambiguous one, we measured its peak brightness near the launching point in the H-band polarized light data and compared it to the azimuthal average of the disk flux at the same separation. We find a spiral-to-disk contrast ratio of 2.29. Assuming aspect ratios of 0.05 and 0.07 and using equation 14 from Dong & Fung (2017) yields planet masses of 0.7 \( M_{\text{Jup}} \) and 1.1 \( M_{\text{Jup}} \), respectively. This is well consistent with the required planet mass to open an eccentric gap. Due to the large distance of the AT Pyx system and the additional confusing disk signal, the thermal radiation of such a planet is unfortunately below our detection threshold.

Alternatively, if scenario 2 holds true with a disk position angle of 0°, then a strong misalignment of the inner and outer disks might also indicate the presence of a perturbing companion, which may be of planetary or stellar nature, similar as in the case of the disk around HD 142527 (Lacour et al. 2016; Price et al. 2018). A relative to the line of sight strongly inclined inner disk may also explain the strong optical variability of AT Pyx, especially if it is highly structured, such that dust clumps can occult the star. Given the location in the head of CG-22, it may also be possible that a relative disk misalignment between inner and outer disk is caused by material infall, similar to that recently inferred in the case of the SU Aur system (Ginski et al. 2021). In this case, it may be possible that the dynamic structures that we observe in the outer disk were also triggered by an infall event, without the need for a perturbing compact object.

The morphology of the AT Pyx system is intriguing and may well present the first detection of dynamic signs of ongoing planet formation in an externally photo-evaporated disk. To confirm this inference, ALMA observations in the submm are needed to determine the basic disk geometry and mass. High-resolution CO line observations may enable us to trace the kinematic signatures of the spiral features seen in scattered light. While a direct detection of the thermal radiation of the embedded planets is challenging with current ground- and space-based instrumentation, it may well be possible to observe accretion signatures, which can be more easily disentangled from disk scattered light (e.g., Haflert et al. 2019).

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Appendix A: SPHERE polarimetric images

In Figure A.1 we present the Stokes Q and U, as well as the derived $Q_\phi$ and $U_\phi$ images. The flux calibration was carried out by measuring the flux of the central star in the noncoronagraphic flux calibration images, taken at the beginning and end of the observation sequence. To convert pixel counts to physical units we used the 2MASS H-band magnitude of AT Pyx as reference. The $U_\phi$ image is showing very low flux levels compared to the $Q_\phi$ image, which indicates that the polarization signal is heavily dominated by single scattering of the light of the central star. This is expected for a circumstellar disk seen under a relatively low inclination, compatible with our analysis.

Appendix B: Cross identification of sub-structures

In order to better cross-identify substructures between the different observational data sets, we present contour overlays of the polarized light H-band data on top of the SPHERE K-band and NACO L-band total intensity data. The structures A1 and A2, as well as S1, S2, and S3 match closely in position and shape between the SPHERE data sets. The NACO data set has lower spatial resolution and contrast close to the star and does not detect features S1 or S3. It does detect the extended ring-like features A1 and A2. We note that feature A1 in the NACO data has a "forked" appearance on the northern end, which is similar to what is seen in the PDI contours and is there caused by the merging of feature S2 with feature A1. In that sense feature S2 might be regarded as marginally detected in the NACO data as well.

Appendix C: Simulated ADI on PDI data

To test whether the non detection of the features A1 and A2 in the IFS data might be a post-processing effect, we simulated classical ADI post processing on the IRDIS PDI H-band data. The result is shown in figure C.1. The ring-like features A1 and A2 are strongly suppressed because they extend predominantly in the azimuthal direction. The spiral-like features S1, S2, and S3 are to some degree visible in the data, but at low S/N. We note that a perfect match with the IFS data set is not to be expected because the IFS data show total intensity while we only use the polarized light as input for the simulation. Additionally, the noise characteristic of IRDIS and the IFS is fundamentally different because the IFS has a higher thermal background due to a lack of cooling. Nevertheless, it is clear that ADI post-processing strongly suppresses the ring-like features in the data.
Fig. A.1. SPHERE/IRDIS H-band polarimetric images of AT Pyx. To highlight all features of the disk the color map is partially logarithmic, starting at $4 \, \text{mJy/arcsec}^2$. All images are shown on the same color scale. Images are aligned with true north up and east to the left. The gray hashed area marks the coronagraphic mask that was blocking the stellar light.
Fig. B.1. SPHERE/IRDIS K-band image after ADI post-processing (same as in figure 3), shown in a logarithmic color map. The white overlaid contours are drawn from the SPHERE/IRDIS H-band Qφ image after high-pass filtering (same data set as shown in figure 3). The contours associated with the features S1, S2, and S3, match closely in shape and position to the position of the same features as seen in total intensity. We note that we display the size of the H-band coronagraph with the gray hashed circle.

Fig. B.2. NACO L-band image after ADI post-processing (same as in figure 2), shown in a logarithmic color map. The white overlaid contours are drawn from the SPHERE/IRDIS H-band Qφ image after high-pass filtering (same data set as shown in figure 3). The contours associated with the features A1 and A2, match closely in shape and position to the position of the same features as seen in total intensity.

Fig. C.1. IRDIS H-band polarized light data set after post-processing by simulated classical ADI. For the field rotation during the ADI simulation the parallactic angles of the IRDIS K-band data set were used. The ring-like features A1 and A2 are strongly suppressed.