New NIR spectro-polarimetric modes for the SCExAO instrument

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ABSTRACT

The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument is equipped with a fast visible dual-camera polarimetric module, VAMPIRES, already producing valuable scientific observations of protoplanetary disks and dust shells. We present two new polarimetric modules that were recently implemented,. using the NIR light from y- to K-band and identical Wollaston prisms to split the polarizations. The fast polarization module follows a design similar to VAMPIRES, with a fast IR camera either the First Light C-RED 2 or a Leonardo SAPHIRA detector that can run at kilohertz frame rates, and a Ferroelectric Liquid Crystal (FLC) device modulating the polarization in a synchronized way with the acquisition. The fast frame rate coupled with the FLC allows to freeze atmospheric speckles and to calibrate more precisely the degree of polarization of the target, as already demonstrated by VAMPIRES. For the second module, we perform spectro-polarimetric measurements at a slower rate, using the CHARIS Integral Field Spectrograph (IFS). The field-of-view is reduced by a factor 2 in one direction to 2x1 arcsec, to accommodate for the imaging of both polarizations on the same detector without sacrificing the spectral resolution of the instrument. This is the first demonstration of a high-contrast spectro-polarimeter using an IFS. We present on-sky results of the new polarimetric capabilities taken

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during the commissioning phase, on strongly polarized targets. In addition, we show future capabilities that are already scheduled to increase the performance of these modules, especially the addition of non-redundant masks, as well as a polarimetric vector Apodizing Phase Plate (vAPP) coronagraph.

Keywords: high-contrast imaging, polarimetry, spectro-polarimetry, adaptive optics

1. INTRODUCTION

The successful recent campaigns looking for protoplanetary disks, transition disks and debris disks with polarimetric modes of SPHERE[1] and GPI[2] demonstrate the power of polarization differential imaging (PDI) for high-contrast instruments. Observing these disks, especially combined with ALMA observations in the sub-millimeter, reveals processes of planet formations, and can even indicate the presence of planets despite being too small to be observed with traditional high-contrast imaging. PDI was an important component of the High Contrast Instrument for the Subaru Next Generation Adaptive Optics (HiCIAO),[3] and produced high-contrast images of about a dozen new disks.[4] It's successor, the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO),[5] is a high-contrast instrument capable of extreme wavefront correction, to achieve deeper contrasts. Its modular design allows to add new capabilities easily, and validate them in the lab and on-sky in a short time.[6] SCExAO was equipped with the VAMPIRES module since its inception,[7] to perform PDI in visible (660-800 nm), sometimes combined with aperture masking for increased resolution. However, until recently, SCExAO was missing the capacity to look at polarized signal in infrared (IR), that HiCIAO used to do. To increase the capabilities of SCExAO to analyse polarized signals, we performed three major upgrades. The first one was to improve the VAMPIRES modules by adding a second science camera for differential imaging, and a fast Ferroelectric Liquid Crystal (FLC). The second upgrade is adding a spectro-polarimetric mode in IR to the CHARIS Integral Field Spectrograph (IFS).[8,9] Finally, the third upgrade focuses on a fast IR PDI mode, similar to VAMPIRES in visible, using a C-RED ONE camera. We present here these three upgrades, and some on-sky results taken during commissioning.

2. VISIBLE DUAL CAMERA POLARIMETRY WITH VAMPIRES

The Visible Aperture Masking Polarimetric Imager for Resolved Exoplanetary Structures (VAMPIRES) is one of the visible modules of SCExAO (600–800 nm), available in open-use for astronomers. The goal is to perform high-resolution measurement of the polarization of sources with great accuracy, using various schemes. The high-resolution part benefits from the correction of the Pyramid Wavefront Sensor (PyWFS)[10] to get images with reasonable Strehl ratios (>20%). The instrument can be used in full pupil mode for classical imaging, or in combination with Sparse Aperture Masks (SAM) for known polarized structures —dust shells, binaries, stellar surfaces— for a factor 2 improvement in resolution. Figure 1 presents an on-sky PSF acquired with VAMPIRES at 750 nm, from a cube of high-speed data recentered and co-added.

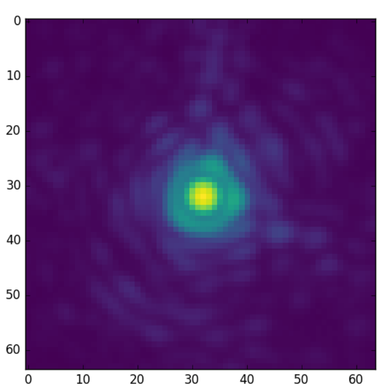


Figure 1. High-Strehl on-sky images taken with VAMPIRES. This image was created from a cube of images taken at high frequency, recentered to remove jitter, and co-added.

The module went through extensive upgrades in the last few years, to improve the speed and precision of the polarization measurement, as well as new modes. Previously, VAMPIRES used only one camera, and an optical assembly to split both polarizations and image both of them on the detector. The main upgrade was the addition of a second acquisition camera, and a polarizing beamsplitter (see Figure 2). Each polarization is now split with the cube, and imaged with a dedicated camera. This allows to sub-window the acquisition, and run faster than before. To compensate for any differential errors between the two cameras, a Ferroelectric Liquid Crystal (FLC) device acts as a half-wave plate that can be synchronized with the cameras acquisition to flip back and forth the polarization state on each camera. Another half-wave plate, located in front of AO188, is also rotated at a slower rate (typically every minute), to calibrate any polarization errors coming from AO188 and SCExAO.

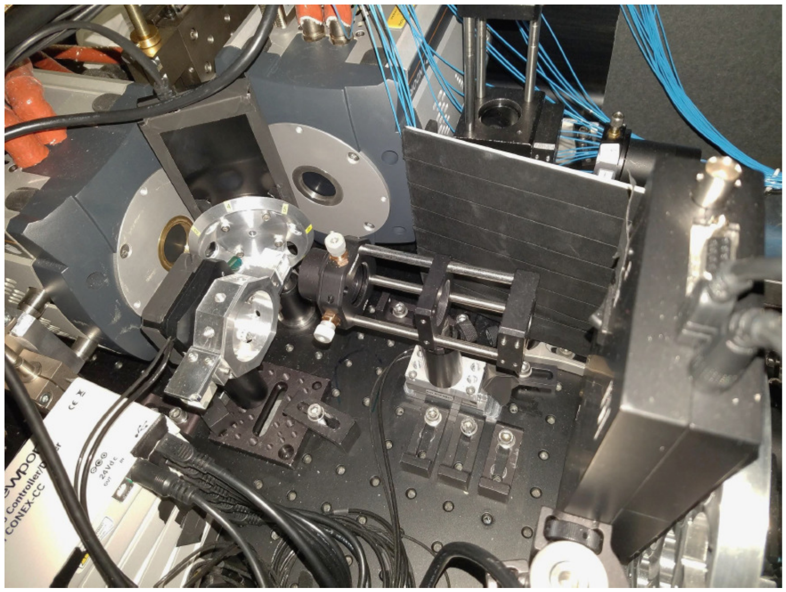
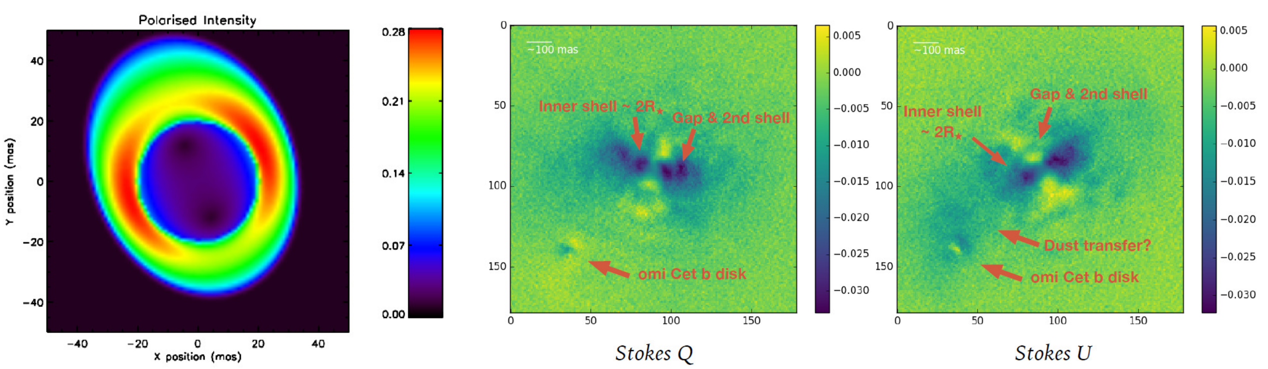


Figure 2. Picture of the VAMPIRES module inside SCExAO. The two cameras are located at the top left, with the differential filter wheel in between, and the beamsplitter cube wheel in front of it.

VAMPIRES has achieved under 10 mas resolution on polarized source, such as the inner mass-loss dust shell around the star μ Cep (See Fig. 3 (a)),[11] or the same type of dust-shell around Mira (o Cet) A, as well as a disk around the white dwarf companion Mira B (see the work in progress on Fig. 3 (b)).



(a) (b)

Figure 3. Two science results from the VAMPIRES instrument. a) Dust shell in polarized intensity around the star μ Cep, showing an asymmetry. b) Dust shell in Stokes Q and U around the star Mira (o Cet) A, and disk of dust around the white dwarf companion Mira B.

3. NIR SPECTRO-POLARIMETRY WITH CHARIS

Combining adaptive optics and polarimetric differential imaging (PDI) allowed to image dozens of protoplanetary disks composed of gas and dust, notably with HiCIAO on Subaru. With Extreme AO, it is possible to go even closer in inner working angle, and image secondary structures and spirals, as demonstrated by IRDIS on SPHERE, and the polarimetric mode of GPI's integral field Unit (IFU). When HiCIAO was replaced by the IFU CHARIS behind SCExAO, we lost this ability of imaging polarization in NIR. Adding a Wollaston prism inside CHARIS similarly to GPI's IFU, where the Wollaston prism is inserted instead of the dispersing prism, is costly and would replace one of the dispersing modes of CHARIS. Thus we decided instead to add a retractable Wollaston prism at the entrance of CHARIS (room temperature), before the cold stop. In this case, we lose half of the field of view, going from 2×2 arcsec to 1×2 arcsec for each polarization, but we gain the unique capability among high-contrast imagers of performing spectro-polarimetric imaging (See Fig. 4).

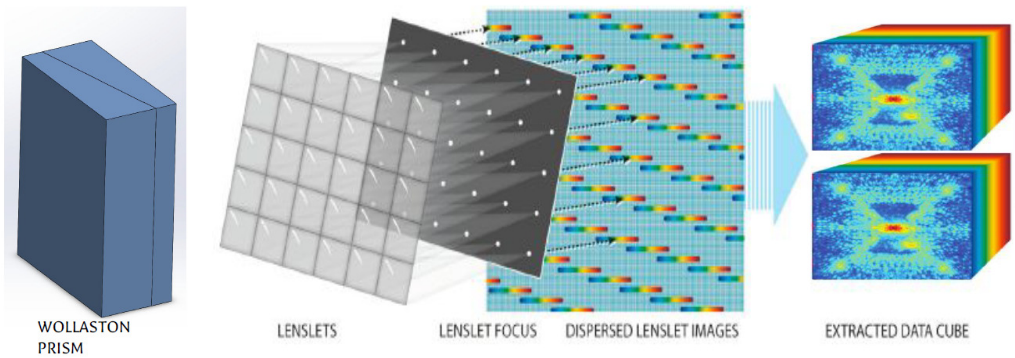


Figure 4. Principle of the spectro-polarimetric mode with CHARIS. The Wollaston splits the two polarizations close to a pupil plane at the entrance of CHARIS, then after entering the Dewar, the light in the focal plane is sampled by a matrix of micro-lenses and an array of pinholes, and dispersed by a prism. The final cube is extracted from the raw image. Each polarization occupy half the normal field of view of CHARIS, i.e. 2×1 arcsec.

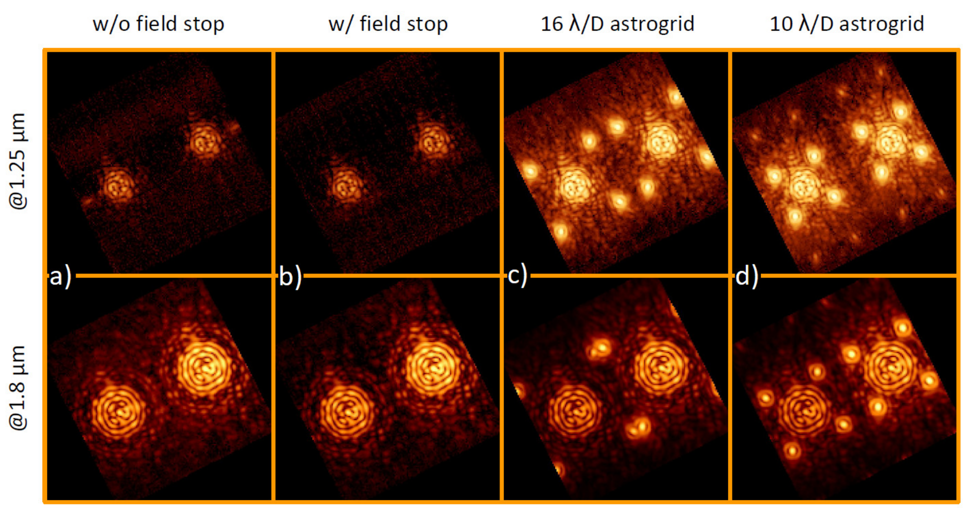


Figure 5. Lab measurements at two different wavelengths (two selected slices in the CHARIS cube), in various conditions. In each case, a Lyot coronagraph with an inner working angle of 113 mas is used. a) Field stop is out, speckles from the quilting of the DM are polluting the polarizations. b) Field stop is in, the quilting speckles are no longer visible. c) Usual speckle grid used with CHARIS, with a separation of 16 λ/D. The separation is too high for the field of view at longer wavelengths. d) A grid with a separation of 10 λ/D is more adapted to the field of view.

The Wollaston prism was designed to split the polarizations evenly with a separation angle of 1 arcsec on sky. A field stop, consisting of a laser-cut carbon fiber rectangle aperture of 2×1 arcsec, was installed on a XY translation stage in the last focal plane before the Wollaston prism. This mask removes any cross-talk between polarizations, as illustrated with the lab data of Fig. 5. This figure presents lab measurements taken with SCExAO's polychromatic internal source, a Lyot coronagraph, and CHARIS. Our internal source has very weak flux in K-band, so the tests were performed only in J- and H-band. When the field stop is out (Fig. 5 (a)), some light from one polarization —here the speckles introduced by the waffle pattern of the DM— can be seen in the other polarization. When the mask is in place (Fig. 5 (b)), this stray light is not visible. Figure 5 (c) and (d) also show that an adaptive speckle grid can still be used for astrometric and photometric calibration, although the regular spacing of 15.9 λ/D is too large and outside the field of view at the end of H-band (Fig. 5 (c)). Thus a smaller separation of 10 λ/D can be used (Fig. 5 (d)).

The new PDI mode was successfully tested on-sky during SCExAO's engineering night of February 26, 2019. The polarization was modulated using the half-wave plate in front of AO188, but since VAMPIRES is using the same device for polarization modulation, it was driving the rotation asynchronously from CHARIS. This means that some of CHARIS images had to be discarded when the half-wave plate was rotating. In future tests, we will synchronize CHARIS and VAMPIRES to avoid this problem. A good validation of the new PDI mode is presented in Fig. 6, which shows a comparison between the PDI images of AB Aurigae using AO188 and HiCIAO,[4] VAMPIRES (processing in progress) and the new mode of CHARIS. This preliminary result shows the same complex disk structure, with asymmetric spiral arms, with a slightly smaller inner working angle for the CHARIS image, compared to HiCIAO. In this image, all the wavelengths were collapsed, but with more processing, a spectrum could be extracted.

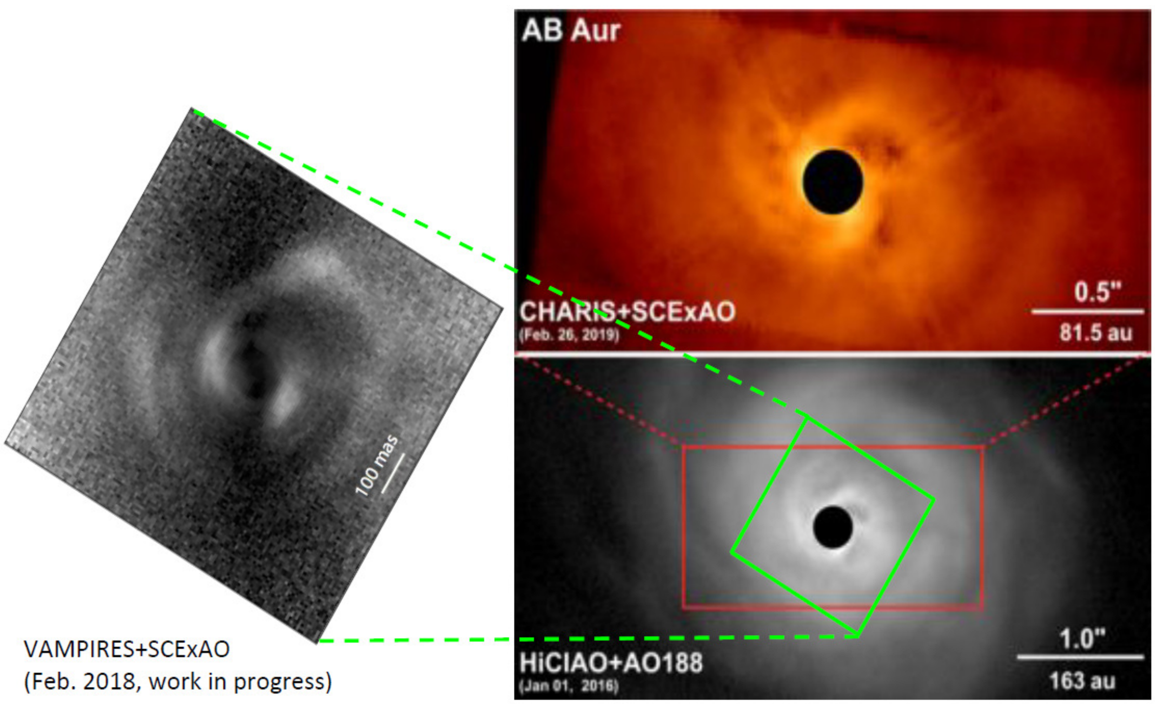


Figure 6. Comparison of the polarimetric intensity images between old HiCIAO observations (2016), and CHARIS observations (2019). In the CHARIS images, the wavelengths were collapsed. The CHARIS image shows a slightly better resolution and inner working angle. In comparison, we also present a VAMPIRES image (work in progress) of the central region. Residual spider diffraction is still visible in the CHARIS image, probably due to uncorrected distortion.

4. FAST NIR POLARIMETRY WITH A C-RED ONE

The second mode that we implemented on SCExAO uses the latest developments in fast and low-noise IR detectors. Similarly to VAMPIRES in visible, we use a FLC to modulate the polarization at the frequency of the acquisition, while a Wollaston prism, identical to the CHARIS one, splits the polarizations on the detector.

The field stop can therefore be shared between CHARIS and this mode, as long as they are oriented the same way. In this case though, the prism can be rotated manually with 45 degree increments. We have therefore four different field stop masks: a horizontal mask, a vertical mask, a 45 deg mask and a 135 deg mask.

The development of this mode is still on-going. The FLC was installed in the instrument just before this conference, synchronization between the detector and the FLC is also on-going. A First Light Imaging C-RED ONE camera was purchase this August, and will be delivered before the end of March 2020.

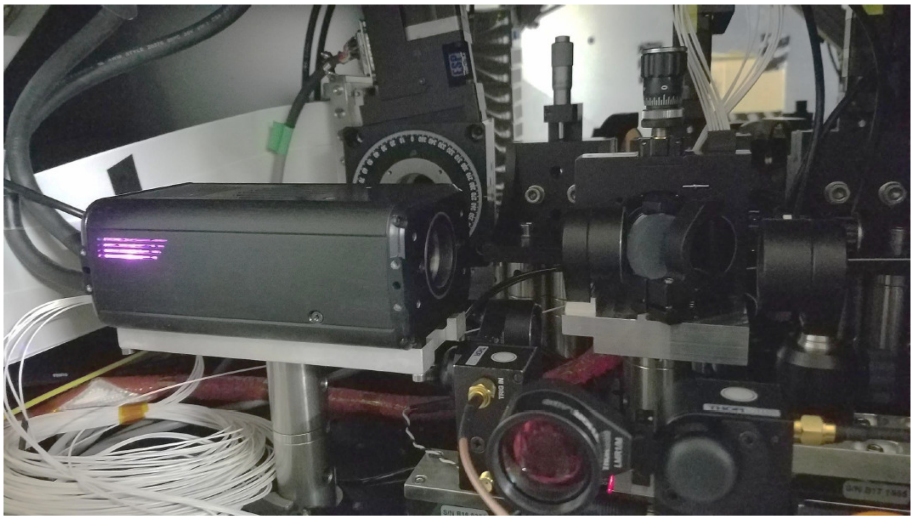


Figure 7. Picture of the internal C-RED2 camera used for the current fast IR polarization mode.

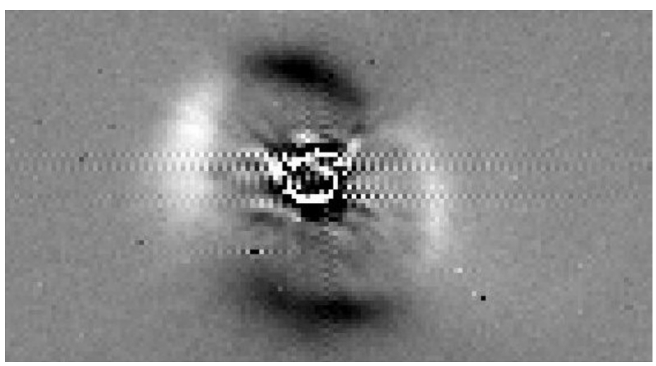


Figure 8. Preliminary processing of on-sky data taken with the internal C-RED2 camera, of the bright HD34700A disk. Only one Stoke mode is shown here.

In the meantime, some testing has already been done on-sky, using the field stop, the second Wollaston prism, and the internal NIR camera of SCExAO, a C-RED 2 (see Fig. 7). A filter wheel is also available on this path, with band filters (y, J and H), and narrowband filters around 1550 nm (50 and 25 nm bandwidth). We looked at various polarized targets, mostly in broadband mode (0.95-1.7 µm). Figure 8 presents an example of PDI processing with the C-RED2 on the bright disk around HD34700A, imaged previously by GPI.[12] The processing was in a very early stage, only on a few seconds of data, and for just one position of AO188's half-wave plate. This result is very promising first step towards a fast IR polarization mode.

In parallel with this effort, over the last few years we tested several fast-IR low-noise cameras: The Institute for Astronomy (IfA) SAPHIRA camera,[13] and Project Kernel's C-RED ONE camera (Figure 9). These two cameras, mounted to a compatible port on the side of SCExAO, were used to test the SAPHIRA technology, measure speckle lifetime,[14] or study innovative Kernel applications.[15] The newly purchased C-RED ONE will also use this port for the fast PDI mode.

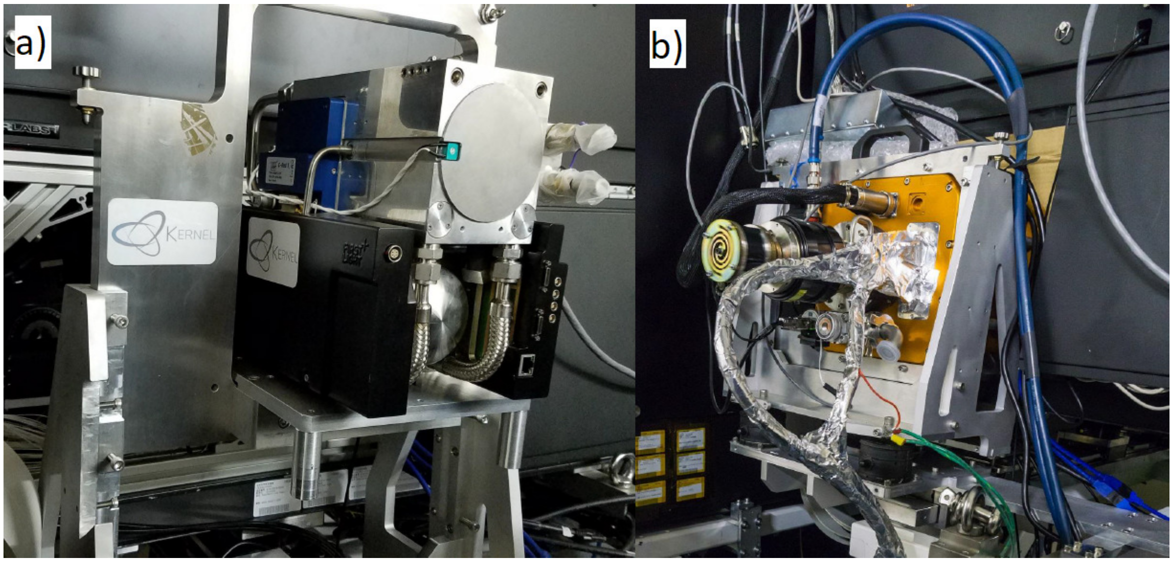


Figure 9. Two fast IR photon-counting camera tested on SCExAO. a) The Kernel camera, a C-RED ONE from First Light Imaging. b) IfA's custom SAPHIRA camera.

5. FUTURE WORK

As we previously mentioned, a few steps are necessary to complete both IR polarimetric modes. For the spectro-polarimetric mode, a synchronization between VAMPIRES and CHARIS has to be set up to optimally move the half-wave plate of AO188 between acquisitions. For the fast IR polarimetric mode, besides the integration of the C-RED ONE that will take a few months, we are working on the synchronization of the acquisition with the FLC, allowing to modulate the polarization at the speed of the camera.

Besides these steps to finish these two modes, future upgrades are already scheduled to add new capacities. Similarly to VAMPIRES, the IR path will be equipped with non-redundant masks (NRM) to gain in resolution for some specific targets. For the fast-IR polarization mode, the masks could be installed in the last pupil plane, after the light is split with the other ports. In this case we could for example do NRM imaging in y-band for the fast-IR polarization mode, and spectro-polarimetric imaging with CHARIS in J to K-band.

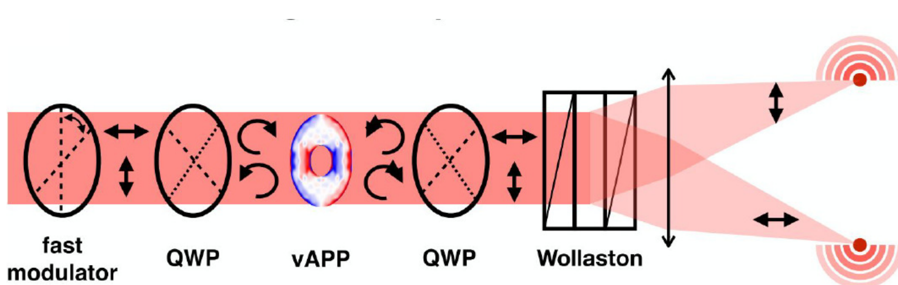


Figure 10. Principle of a polarized vAPP.

The same pupil plane can be used to insert a polarimetric vector Apodized Phase Plate (vAPP).[16] SCExAO is already equipped with a vAPP, where a grating is added to split the two dark zones and image them on CHARIS. The envisioned polarimetric vAPP would not have this grating, the dark zones being separated by the Wollaston prism itself (see Fig. 10). However, the polarimetric vAPP requires circular polarization instead of linear polarization. The mask would then be surrounded by two polychromatic quarter-wave plates.

6. CONCLUSION

Due to its modular design, we can add and improve modules of SCExAO fairly easily. One of the most recent improvements were focused mainly on polarization differential imaging, both in visible and infrared. We updated the VAMPIRES module with a second camera and a FLC, allowing for shorter integration times. In addition, two new IR modes were implemented. A spectro-polarimetric mode using the IFS CHARIS, and a fast IR polarimetric mode similar to VAMPIRES, but this time using a C-RED ONE camera.

The spectro-polarimetric mode is opto-mechanically completed, by adding a field stop and a Wollaston prism in front of the IFS CHARIS. The mode will be soon completed by synchronizing CHARIS and VAMPIRES, since both are sharing AO188's half-wave plate to modulate the polarization state. This mode was already successfully tested on-sky, and will be available in Open-Use starting from semester S20A.

Future upgrades include non-redundant masking and polarimetric vAPP, which will allow us to reach lower resolution and higher contrasts that will allow us to probe inner disks and fainter protoplanetary disks.

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