Suppressing a Sea of Starlight : enabling technology for the direct imaging of exoplanets

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Issue Date: 2016-11-29

7 Outlook

This thesis focuses on the development of the vector Apodizing Phase Plate that overcomes the limitations of the original APP manufacture. The main selling points of the vAPP are its broad-band achromatic behavior from anywhere in the near-UV to mid-IR and the highly customizable phase patterns. In this Chapter we look at the current possibilities with the vAPP and future developments.

7.1 Science observations with vAPP

7.1.1 NIR observations

The first observations with the vAPP at MagAO show an unprecedented contrast close to the star. As presented in Chapter 6 the two vAPP images can be used under rotation, scaling and subtraction to improve the contrast close to the star. We measured a 5σ contrast of 8.3 $(= 10^{-3.3})$ magnitudes at 2 λ/D, 10.8 $(= 10^{-4.3})$ at 2.5 λ/D, 12.2 $(= 10^{-4.8})$ at 3.5 λ/D, and 12.5 $(= 10^{-5})$ at 4.5 λ/D, all derived at 3.9 microns narrow-band.

For a sample of bright nearby young stars (< 100 pc) these contrasts correspond with a detection sensitivity down to 4 M_{Jup} with separations of 4 AU within 3 hours of observations per target. Most of the mass for the formation of planets is available at these separations around stars. Just beyond the iceline around stars it is expected that most of the giant gas planets form. By measuring the occurence rate of giant gas planets at these distances formation models can be constrained.

In the near future we intend to expand our observations of nearby (< 70 pc) young stars (in moving groups) and also explore the increased detection sensitivity (in terms of mass) at M-band with MagAO where even smaller planets can be detected. Based on a limit of 1 λ/D spectral smearing we expect that the following filters in MagAO are usable: $Br\gamma$, [3.1], [3.9], M'. The broader filters are usable but the spectral smearing is significant and needs to be taken into account while interpreting the data.

7.1.2 Broad-band observations

While the design of the vAPP with the included grating is incredibly simple and robust against retardance offsets, it does reduce the maximum width of the filter that can be used for observations. Some telescopes are already equipped with some of the optics necessary to perform achromatic handedness-based splitting and are therefore very suitable to quickly explore this option. MMTpol is a $1-5$ micron diffraction limited polarimetric imager located at the AO-capable 6.5m MMT in Arizona (Packham and Jones, 2008). It has a Wollaston prism that we can use in combination with an achromatic quarter wave plate and a vAPP coronagraph. This is identical to the original optical setup used for our laboratory measurements with the vAPP prototype in Chapter 3. MMTpol already has a rotatable half-wave plate as polarization modulator. This combination of optical components makes it possible to do broadband dual beam polarimetry in the NIR. Note that the retardance offset again becomes a problem in this setup but this effect can be reduced by developing a device with more liquid crystal layers to push the retardance closer to half-wave.

7.1.3 The push towards shorter wavelengths

The vAPP can be optimized for different wavelengths from the near-UV to the mid-Infrared with broad-band achromatic performance. A logical step after demonstrating the broad-band vAPP between $K - M$ band is to apply the coronagraph to shorter NIR wavelengths like J, H, K (resp., $1.25, 1.65, 2.2$ microns) and the filters at the red edge of the visible range r, i, z, y. The transmission of the coronagraph is $\sim 90\%$ in the visible, even for the achromatic multilayer devices, which means that the coronagraph is almost twice as efficient in the visible than in the NIR. Logical contenders for a move to shorter wavelengths are VisAO at the Magellan Clay telescope and ZIMPOL ($V-I$), IFS ($Y-H$) and IRDIS ($Y-K_s$) in SPHERE. Both ZIMPOL and IRDIS are already equipped with polarizing beamsplitters, facilitating the installation of vAPP coronagraphs. For bright ($V < 8$) stars ZIMPOL produces Strehl ratios of 50-70% depending on the filter (Fusco et al., 2014). VisAO at Magellan currently has a Strehl ratio of $> 30\%$ (Close et al., 2014). With the expected upgrades of MagAO with a deformable mirror and increased correction speed (MagAO-X and MagAO-2K) the Strehl ratio in the visible will become even more favorable for direct imaging. Interesting scientific targets in the visible are planetary accretion around young stars in Hydrogen alpha (Close et al., 2014) and the reflected light of planets in the habitable zone around the closest stars, such as Alpha Centauri (Males et al., 2014).

7.1.4 Binary observations with vAPP

Many massive stars reside in roughly equal mass binary systems. These targets are often ignored in direct imaging studies as only select coronagraphs (like the APP) can cope with double stars. Binary Differential Imaging was used by Rodigas et al. (2015) on a wide (4 arcseconds) system to improve the contrast within 1 arcsecond by 0.5 magnitudes with respect to a normal ADI reduction. BDI requires that the PSF is approximately the same across the field of view. This only works without focal-plane coronagraphs and if the isoplanatic patch is large enough to cover both stars. This is easier to achieve in the NIR since the atmosphere has less impact. As it is located in the pupil-plane the vAPP is 100% compatible with this technique and is expected to boost the contrast even more. Further study is necessary to determine the magnitude of this improvement. Rodigas et al. (2015) mention that they are performing a survey of 140 nearby visual binaries with MagAO/Clio2 using the BDI technique. The current presence of the vAPP in Clio2 makes it trivial to confirm the improvement. A second correction step using the rotation, scaling and subtraction method presented in this thesis can be used to improve the contrast. Furthermore, we can design PSF structures such that the far rings of one star do not deteriorate the contrast in the dark hole next to the other star as was proposed by Thomas et al. (2015), and in the case of the 360 degree grating vAPP; applied by Christoph Keller to reduce cross contamination between the two coronagraphic PSFs.

7.1.5 Disk observations with 360 degree vAPP

A 180 degree suppressing coronagraph is not ideal for imaging disks as the complicated asymmetric PSF can disturb the apparent shape of the convolution. In Chapter 4 we also demonstrated that the extreme phase patterns that can be implemented can be leveraged to suppress the starlight in a 360 degree region around the star. This 360 degree dark hole can be used to observe disks around bright stars without significant impact to the shape of the disk, which would happen with the regular asymmetric APP PSF. A 360 degree suppressing coronagraph is currently located in pupil wheel of Clio2. The feasibility of this technique can therefore be easily tested.

7.2 Combining vAPP with complementary techniques

7.2.1 Focal plane wavefront sensing

Focal plane wavefront sensing and the subsequent wavefront correction is important to reduce the noise contribution of quasi-static speckles. The phase sorting-interferometry method by Codona et al. (2008); Codona and Kenworthy (2013) has been previously introduced as a promising solution for this (see also Chapter 2). Its main advantage is that it does not require hardware changes to the telescope. The reconstruction is purely software-based using the wavefront sensor telemetry and rapid science camera images. The reconstructed wavefronts can be applied on the deformable mirror to correct the images.

Several focal plane sensing methods could potentially be implemented in the vAPP coronagraph concept. It is known that wavefronts can be estimated from images with a known phase diversity (Roddier and Roddier, 1993). In the case of the grating-vAPP we have 3 PSFs with a known phase error which potentially can be used to do instantaneous phase diversity wavefront estimation similar to what was proposed for the Vector Vortex Coronagraph (Riaud, P. et al., 2012). The reconstructed wavefront includes the non-common path aberrations and can be sent to the deformable mirror to correct the distortion.

Another method that is being developed in Leiden is the holographic focal-plane wavefront sensing technique by Wilby et al. (2016). A binary phase mask is added to the vAPP phase that projects satellite PSFs around the coronagraphic PSF that are sensitive to certain basic wavefront modes. By measuring the intensity of these satellites the incoming wavefront can be estimated. This method has been demonstrated on-sky at the William Herschel Telescope in April 2015 and will be developed in the coming years.

7.2.2 Spectroscopy

We have already seen that the achromatic nature of the vector APP allows for spectrophotometry with narrow-band filters. The MagAO coronagraph covers 2 to 5 microns using a single optic which reduces the overhead with respect to the old situation where 2 APPs covered only a fraction of this wavelength range. The latter case also required a time-costly realignment of the pupil when switching wavelengths.

To use the full achromatic wavelength range the vAPP can be used in combination with an Integral Field Unit (IFU). The chromatic dependence of the splitting angle can be nullified using the wavelength channels of the IFU. The more conventional setup with an achromatic quarter wave and Wollaston prism keeps all the planet light at the same position. The slit of the spectrograph can be placed exactly across the planet to perform spectroscopy.

A combination of the achromatic vAPP and a fiber-fed high spectral resolution spectrograph can be used to improve the detection of atmospheric signatures through the radial velocity technique as pioneered by Snellen et al. (2014). The contribution of the stellar light to the noise is reduced by the coronagraphic step. In Leiden a dedicated instrument (LExI) is being developed to further explore this concept.

7.2.3 Polarimetry

Due to the polarization-based technology behind some coronagraphs they can be relatively easily adapted to perform polarimetry. Combining polarimetry and coronagraphs is expected to give an improvement for planets with a polarized signal over the contrast achieved by each method individually. Polarized signals can be expected from planets close to the star reflecting starlight at visible wavelengths.

In recent years several coronagraphs have been developed that use these retarding optics. The Vector Vortex Coronagraph (VVC) uses liquid crystals like the vAPP and was introduced by Mawet et al. (2009a,b, 2010). The Annular Groove Phase Mask (AGPM) (Mawet et al., 2005) is related to the VVC but uses sub-wavelength gratings as retarders. Murakami et al. (2012) performed a laboratory study of PDI and ADI with both the VVC and the Eight-Octant Phase Mask, in their case based on photonic crystals. Recently, Snik et al. (2014) presented dual beam polarimetric setups for both the VVC and the vAPP although they did not explore the vAPP with included phase grating. Adapting the grating vAPP for polarimetry only requires the addition of a polarization modulator like a rotatable half-wave plate or Ferroelectric liquid crystal (FLC) in front of the coronagraph. An achromatic quarter-wave plate has to be added between the modulator and the coronagraph to allow the modulation of linear states.

7.2.4 Instruments applying lessons learned

In the short term there are several instruments where we can explore some of the previously mentioned options. There are several logical instruments that can be named, namely: ExPo (Rodenhuis et al., 2012) and LExI, both being developed in Leiden as on-sky technology testbeds to prepare for the next generation of telescopes.

Broad-band vAPP coronagraphs will go to the LBT to replace the current narrow-band version in LMIRCam. One of the coronagraphs will also be optimized for the field of view of the ALES IFU. The vAPP is also being considered for use with VLT/SPHERE and in the near future for the ERIS instrument (Kuntschner et al., 2014); the successor of the very successful NACO instrument at the VLT.

7.3 The vAPP in the ELT-era

We expect that the capabilities of the vAPP will become even more relevant in the era of Extremely Large Telescopes that are planned with diameters of $24 - 40$ meters. The increased sensitivity of the telescopes requires better control of systematics. Vibrations will become an even larger problem with the increased spatial resolution and large mechanical structure, and like with any newly constructed large telescope startup difficulties are expected. A robust and simple coronagraph like the vAPP works under difficult and suboptimal conditions. Its simplicity of manufacturing facilitates a quick adaption to different pupil designs varying from the 7-mirror Giant Magellan Telescope (Johns et al., 2012; Codona, 2004) to the possible annular first phase of the segmented E-ELT. A third ELT that it can be adapted to is the segmented Thirty Meter Telescope (TMT). Adapting focal-plane coronagraphs to work with complicated / segmented pupil designs is not a trivial task and also requires phase and/or amplitude modifications in the pupil (Carlotti, 2013; Ruane et al., 2015). Future instruments behind the ELTs are designed with very broad wavelength ranges and are outfitted with spectrometers and IFUs to take full advantage of this. Current coronagraphs are generally optimized for specific narrow bands. The vAPP coronagraph's achromatic behavior is fundamental for the optimal usage of these instruments. With 100% bandwidth only several coronagraphs are required to span the full spectral range of an instrument. Furthermore, the coronagraph can be optimized from anywhere from NUV to the MIR. A common problem in segmented telescopes like the E-ELT and the TMT is that mirror segments are swapped out to be cleaned. It is expected for these ELTs that several mirror segments will not be in place at any time. Without complicated methods to circumvent the impact to the contrast all coronagraphs will be in theory limited to a contrast level of 10^{-5} [1]. To deal with this ever changing pupil requires flexible adaptive optics and/or adaptive or quickly manufacturable coronagraphs. In light of the expected start-up difficulties with ELTs, and the simplicity and broad-band efficiency of the vAPP, it may very well be the first small inner working angle coronagraph going on-sky in the next generation of telescopes.

7.3.1 European Extremely Large Telescope

The E-ELT has multiple planned instruments that can be used for direct imaging. MICADO will be a $0.8 - 2.4$ micron diffraction limited imager and is a first light instrument (Davies et al., 2010). METIS is a $3 - 19$ micron diffraction limited imager and spectrograph (Brandl et al., 2014). Quanz et al. (2015) simulated the direct imaging performance of METIS on the E-ELT and concluded that Earth-sized planets are in reach of direct detection. In Snellen et al. (2015) the prediction was made that the atmospheric signature of rocky Earth-like planets can be detected in the habitable zone of Alpha Centauri with the combination of high contrast imaging and high dispersion spectroscopy in only one night of observing with E-ELT/METIS. Even the HARMONI instrument (Thatte et al., 2014), while not optimized for high contrast imaging, can accept pupil-plane coronagraphs such as the vAPP. Focal-plane coronagraphs are unavailable in HARMONI due to the uncorrected atmospheric dispersion. MICADO, HARMONI and METIS are all three first-light instruments. The E-ELT instrument EPICS is an dedicated high-contrast imager and is expected to reach a contrast of 10^{-8} to 10^{-9} in the visible and NIR ($600 - 1650$ nm) (Kasper et al., 2010). This makes it possible to detect atmospheric signatures in reflected light from rocky planets. Most instruments planned for the E-ELT can therefore easily accept the simple, robust and achromatic vAPP coronagraph.

The techniques introduced in this thesis are robust and versatile, we will continue to use their

[1] Carlotti during 'Combining Coronagraphs and Wavefront Control' workshop in Leiden

performance in the near future to discover and characterize exoplanets, and to contribute directly to the next generation of telescopes and direct imaging instruments.

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