ADAPTIVE PHASE MASK CORONAGRAPH

Pierre Haguenauer¹,a, Pierre Bourget¹, Dimitri Mawet¹, and Nicolas Schuhler¹
¹European Southern Observatory, Paranal Observatory, Chile

Abstract. High contrast imaging of extra-solar planets and close environments of bright astrophysical objects in general, such as stars or active galactic nuclei, is a challenging task. ELTs and their dedicated AO systems will provide unprecedented high angular resolution. Coronagraphs techniques will allow taking advantage of this resolution, however the technical challenges for coronagraphs are significant (intrinsic contrast, ability to perform over broad wavelength range, inner working angle (IWA) and their design shall be carefully thought to ensure that the capability offered by ELTs are used at maximum potential. Accessing small IWA is considered as an edge as it provides substantial scientific and technical advantages. One of the difficulties of accessing small IWA is that coronagraphs become very sensitive to low-order aberrations such as tip-tilt. Our original approach of adaptive phase-mask (APM) coronagraph aims at integrating the small IWA capability and the mitigation of sensitivity to low-order aberrations within the coronagraph itself. Our concept is applicable to both low and high Strehl regimes, corresponding to current and next generation AO systems. The adaptive coronagraph can adapt dynamically, in quasi real time, to adjust to the observing conditions (seeing, AO correction performances) to deliver a stable and optimized contrast at the science image level.

1. Introduction

The first issue of the Adaptive Mask Coronagraph (APM) was developed to improve coronagraphs observational efficiency ([1]). The concept was using an Hg-mask Lyot coronagraph dedicated for an astrometric survey of faint satellites near Jovian planets ([2-4]). The occulting mask consists of a compressed mercury (Hg) drop with its size controlled to offer an adaptation to the seeing conditions or to the required fraction of the Airy diameter.

Different concepts of phase masks have been developed for coronagraphs in the past few years and have provided high contrast on-sky observations ([5-6] Mawet et al., ApJ, 2010). The advantage of phase masks coronographs is their capability to observe at small IWA, without the limitation of the classical occulting mask as in Lyot coronographs.

The APM was developed following the Roddier & Roddier coronagraph concept ([7]). The amplitude balance of the two phase shifted waves strongly affects the nulling efficiency of a classical phase mask. The balance is mainly affected by: the chromaticity of the Airy disk diameter, the stability of the image centering on the mask and the Strehl ratio. The optimal phase mask diameter is essentially wavelength and bandwidth dependent and must be controlled with high accuracy. The residual low order aberrations from adaptive optics correction will impact the centering and the Airy pattern shape. In our proposed concept, instead of acting on the amplitude misbalance causes, we propose to actively balance the amplitudes by modulating the transmission of the area outside of the phase mask. The real time measurement of the nulling efficiency at the coronagraph output controls the loop error. The liquid-crystal polarization properties provide both the optical modulation and the π phase shift.

a e-mail : phaguena@eso.org
An Hg-Mask Lyot coronagraph and an Adaptive Phase Mask Roddier & Roddier coronagraph working simultaneously in two perpendicular linear polarizations compose the instrument concept. A variable diameter liquid-crystal phase mask is used at the center part, and a modulation of the transmission in the external part of the core.

2. APM precursor concepts and results

Different precursors of adaptive and phase mask coronagraphs are presented in this section. The concepts behind all these coronagraphs have been validated on sky.

2.1. Hg Mask Coronagraph

A Lyot coronagraph with an occulting mask of variable diameter made with a mercury drop has been developed at the 1.6m Ritchey-Chretien telescope of the Laboratório Nacional de Astrofísica in Brazil. It has been used from 2000 to 2004 for an astrometric survey of Neptune and Uranus faint satellites.

The observations were made in the visible using a CCD detector. The large field of view of the camera, 4’ x 4’, allowed to image simultaneously background stars to provide astrometric references. No tip-tilt correction was used in the instrument for these observations. The coronagraph was used to observe the fast motion of the satellites, using thus short exposures from 10” to 1’, without any filters.

Figure 1 presents the used concept for the adaptive coronagraph. An Hg drop is sandwiched between two glass windows. By playing on the distance between the two optical windows, one can adjust the diameter of the drop to adapt to the seeing conditions. The right part of the figure shows the observation of the Neptune satellite Proteus. With the instrument adjusted, one can see the satellite imaged at 5” from the planet, and the obtained contrast is $\Delta V = 12.5$.

![Figure 1](image)

Figure 1 – Left: Hg mask coronagraph concept. Right: observation of Neptune satellite, Proteus, with the adaptive Hg mask.

2.2. Four-Quadrant Phase Mask Coronagraph

Figure 2 (left) presents the working principle of the four-quadrant phase mask (FQPM) coronagraph. The star image is focused on the mask where the phase of the beam is changed. The transparent mask splits the image plane in four quadrants and adds a $\pi$ phase-shift for two of them on a diagonal. This specific design has the advantage of being geometrically achromatic. The Airy disk is focused at the exact crosshair of the mask. The effect of the mask then appear in the new repartition of the light in the next pupil plane: all the light is now concentrated on four identical sections around the original pupil which is now seen as dark. A Lyot stop, slightly undersized compared to the initial pupil dimension allows then to get rid of all the light and allows keeping only the central dark part.

This concept has been used for observation at the 5.1-m telescope at the Palomar Observatory. Figure 2 (right) shows observations of HD148112 in Brγ filter. The companion is at 0.73” from the star, i.e. 2 $\lambda/D$ here. The data analysis and processing allowed obtaining here a contrast of $4 \times 10^{-3}$ (5.9 mag). These observations were made possible thanks to the original concept of the instrument used here (Palomar Well Corrected Subaperture, WCS [8]), which also demonstrated extreme AO capabilities by using the
AO facility developed for the 5.1-m aperture on a 1.5-m subaperture, resulting in a 10-cm aperture spacing. Strehl ratios as high as 94% have been obtained on sky (Figure 3).

Figure 2 – Left: FQPM Coronagraph concept. Right: FQPM sky results, off-coronagraph, on-coronagraph (raw image), on-coronograph image with quadrants subtraction.

Figure 3 – Ex-AO sky results at Palomar. Left: Strehl ratio measured on each individual image. Right: 20s on-sky exposure.

2.3. Vector Vortex Coronagraph

The detailed description of the vector vortex coronagraph (VVC) is given in [9] and [10]. The VVC (see Figure 4, upper-left) is a rotationally symmetric half-wave plate creating a phase screw of the form $e^{i\theta}$, where $\theta$ is the azimuthal coordinate. Opposite phase screws are applied to the two orthogonal directions of polarizations of the incident wave. As for the FQPM, the phase shift applied in the image plane allows sending the on-axis light outside of the pupil in the next plane that can thus be removed by a simple stop.

Laboratory contrasts of $10^5$ over a 15% bandwidth and of $2.10^6$ over a 5% bandwidth have been demonstrated at $3\lambda/D$. Figure 4 (lower-left) shows the detection of a brown dwarf around HR7672 with the VVC used with the Palomar WCS. The observation has been made in Ks filter. The companion is a about $2.5\lambda/D$ from the star and the achieved contrast is around $3.10^4$. The lower-right figure shows the contrasts curves of the VVC on sky: telescope PSF, VVC raw on-sky contrast, and VVC contrast after post-processing using the locally optimized combination of images (LOCI) algorithm ([11]).

The simple concept of the VVC and the availability of its technology make it an extremely powerful coronagraph. Its IWA down to about $1.5\lambda/D$ and its transmission larger than 90% are opening a wide
discovery space, compliant with the specifications of current and next-generation ground-based instruments for exoplanet imaging and characterization such as SPHERE ([12]), GPI ([13]), Palm-3000 ([14]), and HiCIAO ([15]).

![Diagram of vortex phase mask](image1)

![Pupil after VVC for on axis light](image2)

![Detection around HR7672 with VVC, image and cuts](image3)

**Figure 4** – Up left: Vortex phase mask. Up right: Pupil after VVC for on axis light. Lower row: brown dwarf detection around HR7672 with VVC, image and cuts.

### 3. Adaptive Phase Mask Coronagraph

The adaptive and phase-masks coronagraphs presented before have shown the efficiency of these methods for high dynamic coronagraphic observations. The concept of adaptive phase mask presented here is the natural evolution of these techniques. As said earlier, the nulling efficiency of a phase mask coronagraph is highly dependent on the balance of the amplitudes of the two phase shifted waves. The concept proposed here aims at compensating in real time for the amplitude unbalance by modulating the transmission for one part of the shifted wave. The control loop is made by a single avalanche photodiode (APD) at the output of the coronagraph, allowing fast real time response. The measured nulling efficiency and the control loop allows correcting for the effect on the destructive interference of the inadequate phase mask diameter and of the image instability.

The modulation of the transmission is done thanks to liquid crystal polarization properties. The concept of the adaptive phase mask is presented on Figure 5. It will create a “geometrical” or Pancharatnam-Berry ([16]) phase to provide an achromatic $\pi$ phase shift between the core and the external region of the PSF. A first polarizer selects one direction of polarization for the incoming light. The liquid crystals are sandwiched between two optical windows containing the electrodes. The polarization in the core of the PSF is phase-shifted by $+\pi/2$, while it is phase shifted around $-\pi/2$ in the external part of the PSF. Thanks to a second polarizer at the output of the mask, changing the value of the phase shift in the external region around its nominal value allows modulating the amplitude to tune the nulling efficiency.
A series of rings in the center part of the mask is used to adjust the diameter of the central part and tune the system to changing seeing conditions.

Figure 5 – Adaptive Phase Mask concept.

Figure 6 – Double stage APM concept.
Figure 6 presents the concept of the APM coronagraph using the mask described in the previous paragraph. A two stage APM is implemented here to remove the effect of the central obscuration that would otherwise reduce the performances of the instrument ([17]). It allows reducing the residual light leakage without sacrificing the transmission in the coronagraph. The first stage is active with a modulation of the transmission. A reversed rotation of the polarization is applied at the second stage by exchanging the orientation of the twist applied to the nematic liquid crystals. This second stage is passive and only used to remove the light leakage due to the pupil central obscuration. On the right side of the figure, the light repartition in the different image and pupil planes is shown to illustrate the coronagraphic process.

Figure 7 illustrates the advantage of the modulation of the transmission in the coronagraph. The contrast for the peak of the Airy pattern (left plot) and for the rings from the first until the 10th (right plot) is shown vs the tilt (0 to $\lambda/D$ over the horizontal axis) and the transmission of the outer “donut” region of the mask (vertical axis). These simulations have been done for a phase mask of diameter $0.5\lambda/D$, slightly smaller than the one that will provide a perfect theoretical amplitude balance. The optimal nulling efficiency of the phase mask for zero tilt is obtained for a 95% transmission outside of the phase mask in that case. As it can be seen on the figures, when the tilt increases, the control of the outer region transmission allows mitigating the degradation of the contrast.

4. Conclusions

We have presented a new concept of coronagraph, aiming at providing adaptive capability to the observation conditions, with adaptability of the mask in both size and phase. The flexibility of the use of the geometrical phase and dynamically driven liquid crystals enables a whole new kind of coronagraphs design. High band pass for the real-time control of the adaptive system control is provided by the APD and liquid crystals properties. The chromatic effect of the phase shift is minimized using the geometrical phase.

A second version of the concept is already being studied. The segmentation of the outer region in pie charts will provide the capability to modulate, in phase and amplitude, localized areas of the image or pupil plane and may be used to help discriminate between speckles and companions. The temporal modulation enabled by this technology can be associated to synchronous detection techniques to help retrieving low contrast signals ([18]).
5. References