Vector Vector Vortex Coronagraph for space-based and ground-based telescopes

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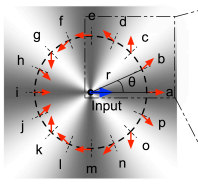
Vector(ial) Vortex Coronagraph (VVC)

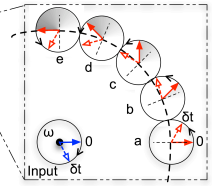
VVC = rotationally symmetric halfwave plate

A. Linear Polarization



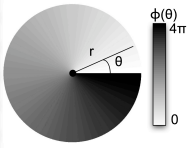
Rotationally symmetric HWP with an optical axis orientation that rotates about the center (dashed lines perpendicular to the circumference). The net effect of a HWP on a linear impinging polarization is to rotate it by −2α where α is the angle between the incoming polarization direction and the fast optical axis. An incoming horizontal polarization (blue arrow) is transformed by the vector vortex so that it spins around its center twice as fast as the azimuthal coordinate θ (red arrows). The background pattern shows the calculated periodic modulation of the intensity transmitted by a VVC between crossed linear polarizers.

B. Circular Polarization



For circular polarization (a circular polarization can be viewed as a linear one rotating at angular frequency ω), the output field rotation is strictly equivalent to a phase delay (the starting point 0 is rotated; therefore phase shifted).

C. Phase ramp: ϕ(θ) = 2θ



D. FT[$e^{i2\theta}$ PSF]

Focal plane → FT → **Pupil plane**

The angle of local rotation of the polarization vector corresponds to a "geometrical" phase: upon a complete rotation about the center, it has undergone a total 2 x 2π phase ramp, which corresponds to the definition of an optical vortex of topological charge 2 (*):

Upon propagation from the focal plane to the subsequent pupil plane, the Fourier transform (FT) of the product of the PSF by the azimuthal phase ramp sends the light outside the original pupil area.

(*) The factor 2 before the azimuthal coordinate in $e^{i2\theta}$ is called the "topological charge" l. It determines the polarization spin rate, and the subsequent height of the phase ramp after a full 2π rotation.

An attractive coronagraph

Pros:

+ small and simple
same layout as for the classical Lyot coronagraph, no apodizer needed

+ small inner working angle
~ 1 λ/d

+ high throughput
> 90%

+ no dead zone
unlike the FQPM (phase discontinuities at the quadrant transitions)

+ maximal discovery space
complete 360° around the center

Cons:

- sensitivity to low-order aberrations
mitigated by increasing l (θ)

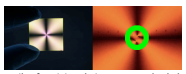
- sensitivity to central obscuration
=> SEE Mawet's POSTER

- chromaticity
=> SEE Mawet's POSTER

Technological Breakthrough

Mawet et al. 2009a, Opt. Express

Implementing the rotating HWP ?
Need a malleable birefringent material.



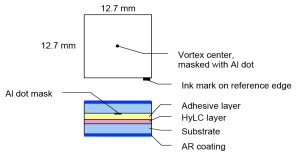
JDSU's Liquid Crystal Polymers (LCP):

- Birefringent ;
- Liquid => malleable ;
- Curable => solid state ;
- Stable.
- LCP Technology limited to visible and near-IR (see Absil's poster and Delacroix's talk about mid-IR)

Generation 0 prototype between crossed polarizers: Compliant except central region of disorientation.

Current device highlights

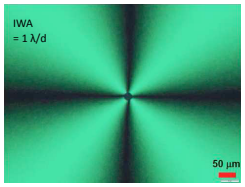
- Central confusion zone <25 microns ;
- Covered with an opaque spot (Al mask, OD>6) ;
- H and K l=2 samples (Palomar) + 2 l=4 samples centered at 784 and 800 nm (HCIT-ACCESS).

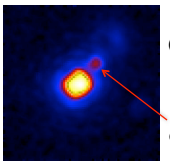


Infrared demo (H and K)

Mawet et al. 2010, ApJ

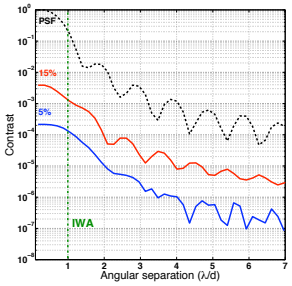
Test of near-infrared devices of topological charge 2 on the IRCT





Contrast @ 2λ/d (15% BW): ~ 5 10^{-5}

Companion detection demo: 5 10^{-4} companion detected @ 2.5 λ/d

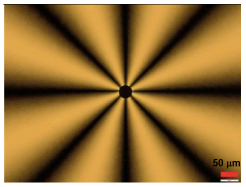


Ready for ground-based telescope (with ExAO)

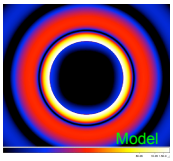
Optical HCIT demo (~ 800 nm)

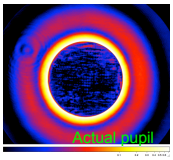
Mawet et al. 2009c, Proc SPIE

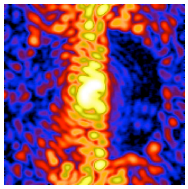
Test of optical device of topological charge 4 on the HCIT

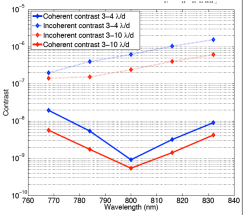


HCIT pupil imaging





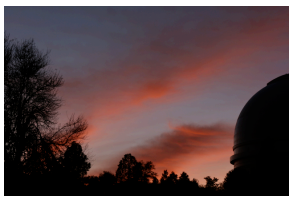




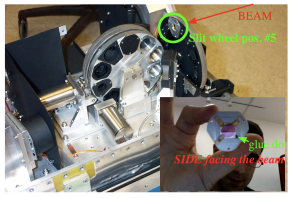
First set of measurement:
Dark hole (10% BW): 2.4 10^{-7}
@3λ/d (2% BW): 2 10^{-7}
Measured half-point (IWA): 1.8 λ/d

Dominated by incoherent light:
Contrast in probe-reconstructed images ~100 x better

Installation at Palomar (many thanks to Jeff)

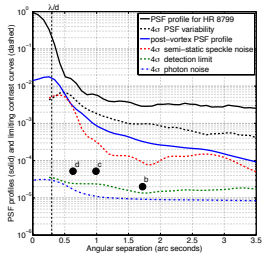


200-inch dome at Sunset



The near-infrared camera PHARO, ready to welcome the VVC

On-sky results, demonstration of contrast and inner working angle capabilities of the VVC

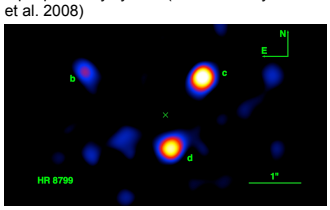


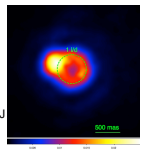
First successful on-sky demonstration of the simultaneous use of all the state-of-the-art high contrast imaging techniques envisioned for SPHERE-GPI and ELTs to study exoplanets:

1- XAO (*) ;
2- Vector Vortex Coronagraph ;
3- mas-level pointing stabilization ;
4- NCPA calibration and active compensation (MGS) ;
5- ultimate image post-processing techniques (LOCI) ;
6- (Spatially filtered WFS)

(*) 1.5 m Well Corrected Subaperture effort:
- Serabyn E., Wallace, K., Troy, M., Mennesson, B., Haguenauer, P., Gappinger, R., & Burruss, 2007, ApJ
- Serabyn, E., Mawet, D., Liewer, K., Bloemhof, E., Haguenauer, P., Mennesson, B., & Wallace, K., 2009 , ApJ
- Mawet, Serabyn, Stapelfeldt, Crepp, 2009b, ApJL

HR 8799 (Serabyn, Mawet, Burruss 2010): triple planetary system (discovered by Marois et al. 2008)





Star XXX: substellar companion detected at 1 λ/d (Mawet et al., in preparation) !!!

Perspectives

Generation 2&3 under manufacturing, our goals are to push the VVC-LCP technology to its limits to reach the requirements of a space-based mission dedicated to planet finding and characterization (e.g. ACCESS, TPF-C), as well as making this coronagraph available for use at major ground-based observatories equipped with (extreme-) AO (VLT, Keck, Gemini, Subaru). Extremely large telescopes are also envisioned (EELT, TMT).

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