High contrast imaging with the L-band vortex coronagraph at Keck/NIRC2

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4 microns: sweet spot for exoplanet imaging

β Pictoris planet and disk with VLT-NACO L-band vortex (Absil et al. 2013, Milli et al. 2014)
Other famous examples

HD106906
Bailey et al. 2013

HD95086 with NACO (L')
Rameau et al. 2013
Another low-mass companion around disk-bearing star

The best demonstration
Macintosh et al. 2015

Fig. 2. 51 Eri b J and H band spectrum from GPI data after PSF subtraction. Strong methane absorption, similar to Jupiter, is readily apparent. Top: The hotter young planetary object 2M1207b and a high-mass field T6 brown dwarf from the SpeX library are overplotted. Bottom: Observed J and H spectrum and Lp photometry with two model fits overlaid, a young low-mass partly-cloudy object (TB-700K) and a higher-mass cloud-free object (SM-750K). Note that the main source of error in the extracted spectrum is residual speckle artifacts, so errors in neighboring spectral channels are strongly correlated; error estimation is discussed in (28).

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Reason #1: lower contrast

![Graph showing contrast with respect to a G2V star across different wavelengths and temperatures.]

- 1600 K (Beta Pic b)
- 1000 K (HR 8799 cde)
- 700 K (max T for cold-start)
- 400 K (max T at 5 Gyr)
- 130 K (Jupiter)
Reason #2: better image quality... for free
Caveats

- Increased sky background:
  \[ L = 16 - 18 \ 5\sigma \] point source sensitivity in 1 hour at Keck
  (cooling the AO bench would help)

- Loss in angular resolution:
  \[ \Rightarrow \text{use of small inner working angle coronagraph} \]
Vortex coronagraph in a nutshell

\[ e^{i/l\theta} \]

\[ l = \text{topological charge (winding number)} \]
\[ = \text{height of the screw dislocation} \]

Mawet et al. 2005

Perfect on-axis cancellation
Annular Groove Phase Mask

- Rotationally symmetric half-wave plate made of sub-wavelength (aka zero-order) gratings
- Small IWA, 360° discovery, can be made achromatic, drop-in device

Mawet et al. 2005
State-of-the-art micro-technology

- First N- and L-band AGPMs
- Peak rejection measured at L band
Deployment at major observatories

2013 (L)  |  2015 (L+M)
LMIRCam

NIRC2 2015 (L+M)

2012 (L)  |  2012 (N)
NACO

VISIR
Commissioning of L-band vortex coronagraph on Keck NIRC2
People and logistics


- **Keck AO team**: B. Femenia, R. Campbell, S. Lilley, D. Chan, H. Tran, S. Ragland, and P. Wizinowich.

- Support at **University of Liege**: lab mask testing (A. Jolivet, C. Delacroix), modeling (B. Carlomagno).

- **Commissioning dates**: 2015-06-08 to 2015-06-10 (3 full nights).

- **Conditions**: excellent with average seeing ~0''.5, only 1 hour lost to fog.
AO performance on typical targets

- Excellent AO performance and stability (not a single AO glitch recorded in 3 nights!),

  => L-band Strehl ratio consistently in excess of 85% (!), peaking at 88% (95% recorded at subsequent run).

  => L-band image quality and stability verified to R~12.5 (M-dwarf), not pushed to the limits yet.
Trade-off between efficiency and performance

- Acquisition time on the vortex and automatic pointing loop ~2-3 minutes.
- Demonstration of nominal on-sky vortex performance.

=> ~50:1 peak starlight rejection, limited by AO residuals
QACITS: automatic centering & scripting of observing sequence
Performance

- Demonstration of pupil-stabilized reference star differential imaging (RDI), aided by minimal overheads during re-acquisition on vortex

  => Enables small IWA science, using the vortex coronagraph at its maximum potential

- Contrast performance maintained and verified from R~2.5 up to R~12.5 (M4 at 15 pc).

Mawet et al. 2015, in preparation

Debris disk discovery
Future work

❖ Optimize pupil registration/Lyot stop alignment
❖ Improve image quality through advanced focal-plane wavefront control with speckle nulling (M. Bottom).
❖ Mode ready for prime time.
❖ From PI-based technical demo to facility:
  => Streamline all processes, open-source pipeline, documentation.
Speckle nulling: from Palomar to Keck
Implementation on-going, commissioning in October 2015

This is a gif movie

M. Bottom (Caltech), E. Huby (ULg), D. Mawet
Core Science: planet formation around low-mass stars
with Henry Ngo, Brendan Bowler, and many others

New unique sample of young M-dwarf (B. Bowler)
1st-generation survey: low-hanging fruits at large separations

Figure 4: Results from our end-to-end model and sensitivity analysis. Top left: average sensitivity of first-generation survey at near-infrared wavelength (H and K bands), adapted from Bowler et al. 2015(6). Top right: our average sensitivity in 30 minutes (open shutter time). Bottom: our average sensitivity in 60 minutes (open shutter time).

References
2nd-generation survey: pushing in!

Ground-breaking sensitivity thanks to L-band and coronagraph
Survey status