Apodized Pupil Lyot Coronagraphs for Arbitrary Apertures

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Context

GPI and VLT/SPHERE deployed on sky!

- Exoplanet direct imagers use diffraction suppression systems
- APLC: coronagraph on sky in P1640, GPI and SPHERE
- Exploration of novel designs for future missions

Update on coronagraph performance, see A.-L. Maire (SPHERE) and L. Pueyo (GPI)

Macintosh et al. 2014, ESO/Beuzit et al. 2014
Lyot coronagraph: formalism

Lyot plane field amplitude

\[ \Psi_C(r) = \Psi_A(r) - (\Psi_A(r) * \hat{M}(r))P(r) \]

Perfect on-axis star image cancellation if both terms match.

How to match them?

Sivaramakrishnan et al. 2001
2 approaches for improvement

- Band-limited mask
- Pupil apodization

Focus on pupil apodization

Kuchner & Traub 2002
Aime et al. 2002, Soummer et al. 2003
Prolate apodizations

- Eigenvalue problem
  \[ \Psi_A(\mathbf{r}) = P(\mathbf{r})\Phi_0(\mathbf{r}) \]
  \[ \Psi_C(\mathbf{r}) = (1 - \Lambda_0)\Phi_0(\mathbf{r})P(\mathbf{r}) \]

- No total extinction solution for APLC but...
- Prolate functions approach this perfect solution

Soummer et al. 2003, 2005
Solutions for arbitrary apertures

- Generalized prolate spheroidal apodizers exist for any aperture geometry and focal mask diameter

- Lyot stop geometry, same as entrance pupil

Martinez et al. 2007
Soummer et al. 2009
Sivaramakrishnan & Lloyd 2005
Apodizer implementation

- Microdots (halftoning process)

- Pupil remapping (Phase-induced amplitude apodization, PIAA)

Martinez et al. 2009 a,b, 2010
Sivaramakrishnan et al. 2009, 2010
Guyon et al. 2003-2014
Traub & Vanderbei 2003, 2005

Nearly 100% throughput,
100% search area, small IWA (< 2\lambda/D)
Quasi-achromatic solutions

- Quasi-achromatic solutions exist for large enough mask (e.g. with GPI with $5.6\lambda/D$ mask diameter)

GPI design: contrast $> 1\times10^7$ at $5\lambda/D$ with central obstruction and 20% bandpass

Soummer et al. 2011

How to gain in terms of IWA and contrast?

Quasi-constant eigenvalue for mask size $> 5.5\lambda/D$, same eigenfunction
Prolate optimization approach

Current approach:
- Optimization metric
  - Final broadband contrast
- Degrees of freedom
  - Prolate apodization
  - Lyot stop geometry

GPI case: $10^7$ contrast at 0.2” ($5\lambda/D$) over 20% spectral bandwidth

how to reach higher contrasts and smaller IWA over a large spectral band?
Shaped pupil type optimization approach

Optimization goal: broadband coronagraphic PSF with dark hole

Kasdin et al. 2003, Vanderbei et al. 2003, Carlotti et al. 2011
Pueyo & Norman 2013

• Linear optimization approach:
  ‣ Optimization metric
    - Throughput
  ‣ Degrees of freedom
    - IWA
    - contrast
    - bandpass
    - Lyot stop geometry

Which apodizer to get this broadband star image?
Prolate apodization with SP approach

- APLC designs using prolate apodizations are recovered with our linear optimization method
- Investigation of novel designs
Parameter space exploration

Existence of solutions for $\rho_i$ (dark zone inner edge) < $m/2$ (mask radius)
Increased robustness to low-order aberrations

- Coronagraphic PSF core is smaller than focal plane occulting mask
- Solutions quasi-insensitive to jitter and low-order aberrations
- N’Diaye et al. for 1D solutions (submitted)
- N’Diaye et al. for 2D solutions (in prep)

What about 2D solutions?
APLC/Shaped Pupil hybrids

- Shaped pupils, see Carlotti’s talk
- APLC with 2D shaped pupil, circular FPM and Lyot stop
- N’Diaye, Carlotti et al. in prep in collaboration with Princeton team

• Tradeoff bandpass, mask size, Lyot stop geometry and dark zone inner/outer edge under study
Conclusion

• Apodized Pupil Lyot Coronagraph
  ‣ Adopted solution on ground-based instruments
  ‣ Developments of novel solutions also viable for space missions (AFTA, see Princeton team’s talks)

• Novel designs in progress (N’Diaye et al. 2014)
  ‣ robustness to low-order aberrations
  ‣ Combination hybrid APLC/Shaped pupil for complex apertures

• Designs for HiCAT (ATLAST-like pupil, work in progress, N’Diaye et al. 2014)
Extra slides
Monocho APLC solutions

Pueyo & Norman 2013: approach similar to Shaped Pupil type optimization (Kasdin et al. 2003, Vanderbei et al. 2003, Carlotti et al. 2011)

- **Linearity** of the coronagraphic field with input pupil function $P$
  - definition of $P$ as a linear combination of modal functions
  - optimization problem with constraints

- Find the optimal modal coefficients to maximize the apodizer throughput s.t.
  - $\text{Max}(P) = 1$
  - Contrast $C$ between $\rho_i$ and $\rho_o$
  - bound on the apodization derivative

- PSF dark zone in monochromatic light with
  - large obscured telescope
  - small IWA ($4\lambda/D$ and below)
  - high contrast ($10^{10}$ and beyond)
Broadband APLC solutions

- Linearity of the coronagraphic field with the input pupil function at any wavelength and for undersized Lyot stop

- Find the optimal modal coefficients to maximize the apodizer throughput s.t.
  - Max(P) = 1
  - Contrast C for
    - separations between $\rho_i$ and $\rho_o$
    - wavelengths $\lambda$ between $\lambda_0 \pm \Delta \lambda / 2$
  - bound on the apodization derivative

Exemple of design for GPI with K-band mask $m/2 = 3.48 \lambda_0 / D$

Coronagraphic intensity profiles at $11 \lambda$

N'Diaye et al. submitted