The synergy between optical interferometry and imaging

Olivier Absil
University of Liège
Outline

❖ Imaging vs. interferometry
  ❖ Similarities, differences
❖ Synergy: illustrations
  ❖ Protoplanetary disks
  ❖ Debris disks
  ❖ Extrasolar planets
Imaging vs. interferometry

One challenge, two cures
Two names for one phenomenon

- Diffraction + interference at the root of image formation
The borders of their realms

- Angular resolution: $\lambda/2B$
- Field-of-view limited by bandwidth smearing and/or use of fibers
- Angular resolution: $1.22 \lambda/D$
Where’s the limit?

Interferometer?

Single aperture?
A continuum of angular resolution
Image or model?

- Image: constrains the surface brightness
- Forward modelling: constrains model parameters

Milli et al. 2014
Model or image?

- Model-fitting interferometric observables (V2, CP)
- Image reconstruction: surf. bright. / forward modeling

Kluska et al. 2014
For the normalization constants we performed the following visual, iterative adjustment. Starting with the flux ratios implied by the values from Table 2 (0.391, 0.443, and 0.474 for F435W, F606W, and F814W, respectively), we adjusted the scaling until the subtraction residuals were minimized. This occurred for normalization constants 0.383, 0.382, and 0.387 in F435W, F606W, and F814W, respectively. Visually, the uncertainty of these normalization values is 3%, and in what follows we propagate this error linearly (as a systematic error) to estimate uncertainties in calculated quantities (x 3.4).

The values of the normalization constants are consistently lower than implied by the values quoted in Table 2, as expected by the mismatch between the colors of the PSF reference star HD 129433 and those of its spectral model. After subtracting the coronagraphic images of HD 129433 from each image of HD 100546, we corrected for the geometric distortion in the HRC image plane, using the coefficients of the biquartic polynomial distortion map provided by STScI (Meurer et al. 2002) and cubic convolution interpolation to conserve the imaged flux. By using standard IRAF routines, we aligned the two rolls in each band, using other stars in the field for reference.

The values of the normalization constants are consistently lower than implied by the values quoted in Table 2, as expected by the mismatch between the colors of the PSF reference star HD 129433 and those of its spectral model. After subtracting the coronagraphic images of HD 129433 from each image of HD 100546, we corrected for the geometric distortion in the HRC image plane, using the coefficients of the biquartic polynomial distortion map provided by STScI (Meurer et al. 2002) and cubic convolution interpolation to conserve the imaged flux. By using standard IRAF routines, we aligned the two rolls in each band, using other stars in the field for reference.

The approximate size of the coronagraphic mask is shown as a black circle 1.00 arcsec in radius. The top row has a different color stretch and spatial scale than the other two, in order to showcase different regions. The top stretch goes from 10$^{-5}$ to 10$^{-3}$ arcsec$^{-2}$. The middle and bottom rows show from 10$^{-5}$ to 10$^{-3}$ arcsec$^{-2}$. The contours in the bottom row are obtained from images that have been heavily smoothed. The contour values are (2; 3; 4; 5; 6; 7; 9; 12; 15; 10$^{-5}$ arcsec$^{-2}$).

**Protoplanetary disks**

Planetary formation at all scales
Synergy in a nutshell

Dullemond & Monnier 2010
The case of HD100546

- Herbig Be star at 97pc
- One of the first «transition» disks
- Gap suspected (1-10 AU)
- Spiral arms detected in visible and near-IR images of the outer disk
NIR interferometry

- Tenuous inner disk of small grains, peaking at 0.25 AU, coplanar with outer disk
- Gap confirmed up to 13 AU, possibly opened by planet
- Inner disk rim probably not puffed up
MIR interferometry

- Sensitive to warm dust, including inner rim of outer disk
- Inner rim = (asymmetric) bright ring at 11±1 AU
- Curvature of inner wall constrained
  - Hydro simulations suggest massive gap-clearing BD
- Upper limit of 0.7 AU for innermost disk

Mulders et al. 2013
Polarimetric differential imaging

- Disk resolved down to 0.1″ (10AU) with NACO
- Outer radius of inner gap constrained to 14±2 AU
- Asymmetric brightness profile along minor axis (preferential backward scattering)
- Polarization degree suggests grains larger than ISM grains
- Possible hole

Quanz et al. 2011
High contrast imaging

- L-band coronagraphy reveals compact emission at 0.48"
- Deprojected separation ~ 68 AU
- Position corresponds to polarimetric hole
- Contrast ~ 9 mag
- Slightly extended
- Possible forming planet?

Quanz et al. 2013
Big picture

Avenhaus et al. 2014
Debris disks

Faint disks around bright stars
Outer disk

Kalas et al. 2008

Stapelfeldt et al. 2004
A double inner disk

Absil et al. 2009
Mennesson et al. 2013
Lebreton et al. 2013

VLTI, K band

K band

N band
Spin-orbit alignment

Le Bouquin et al. 2009
Consequence on the grains

Min et al. 2010
Substellar / planetary companions

Reaching the highest contrasts

beta Pic — Absil et al. 2013
The interferometric view

- Double fringe packet
- How to measure the phase?

$\lambda/2B$
The closure phase

- Closure phase not affected by telescope-specific errors
  \[ \psi_{123} = \phi_{12} + \epsilon_1 + \phi_{23} + \phi_{31} - \epsilon_1 \]
- Not biased by turbulence
- Asymmetric objects: \( \psi_{123} \neq 0 \)
- Sensitive to companions
  \[ \psi_{123} = \rho (\sin \alpha_{12} + \sin \alpha_{23} + \sin \alpha_{31}) \]
- Proportional to flux ratio
  \[ \rho = 1\% \implies \psi_{123} \sim 1^\circ \]
Result: \( \chi^2 \) map

Best fit: \( 1.8 \times 10^{-3} \pm 1.1 \times 10^{-3} \) at 14 mas
Detection limits

- VLTI (K band)
- NACO+SAM (L)
- NACO+AGPM (L)

Graph showing detection limits at 15 M\textsubscript{Jup}, 50 M\textsubscript{Jup}, and 1 M\textsubscript{Jup}.
Conclusion: I’ll have both!