VLT-I and Keck:
Infrared Interferometry from the Ground

Rafael Millan-Gabet
Caltech/Michelson Science Center

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Outline

- Introduction
  - Motivation for optical interferometry
  - Basic principles & observables
  - Limitations from the ground
  - Some historical background
- New Generation Large Optical Interferometers
  - Basic characteristics of the VLT-I & KI
  - Instrumentation and science drivers
  - A few science highlights from the VLT-I and KI
  - Next generation VLT-I & KI instruments
- Conclusions & On to Space ...
Why Optical Interferometry?

Coherently combine the light from 2 or more separated telescopes.

**Single Telescope:**
- Diameter: $D$
- Sensitivity $\propto D^2$
- Resolution $\propto \lambda/D$

**Example:**
- 45 mas
- ($D=10m$, $2.2 \mu m$)
- (and perfect AO!)

**Interferometer:**
- Baseline: $B$
- Sensitivity $\propto D^2$
- Resolution $\propto \lambda/B$

**Example:**
- 5 mas
- ($B=85m$, $2.2 \mu m$)

For a given technological limit to single telescope size (e.g. 30-100m for next generation ELTs), it will always be possible to build a larger interferometer providing finer angular resolution (but likely with less sensitivity).
Illustrative Example

Planet-forming (probably) disks around young stars ...

HST resolves large scale disk structure (10-100s AU); while only an optical interferometer can “probe” the inner-most disk regions (sub-AU; e.g. 5mas @ 150pc = 0.7AU).
How Does it Work?

- Form interference fringes with the light from 2 (or more) telescopes.
- Measure their amplitude (and phase); they are the amplitude and phase of the complex “visibility function”.
- The amazing fact:

\[
\hat{V}_\lambda(u,v) \iff I_\lambda(\alpha, \beta)
\]

Measured visibilities at spatial frequencies \((u,v)\) given by source-baseline geometry.

Object brightness

Credit: A. Glindemann - VLTI Tutorial
Limitations (most due to being on the ground)

- Limited \((u,v)\) coverage.
- Turbulence in Earth’s atmosphere destroys the fringe phase.
  
  No direct imaging
  
  ✓ Model fitting (a.k.a parametric imaging).
  
  ✓ With 3 or more telescopes, can also measure the “closure phase” (immune to atmospheric effects) and perform image synthesis (as in radio).

- Telescope size limited to atmospheric coherence area.
  
  \((10 - 50 \text{ cm, for } \lambda = \text{ vis - NIR})\).
  
  ✓ Unless each telescope is AO equipped.

- Integration times limited to atmosphere coherence time.
  
  \((10 - 50 \text{ msec, for } \lambda = \text{ vis - NIR})\).
  
  ✓ Unless a bright reference object is used to stabilize the fringes on the science target (“OPD AO”).

- Sensitivity comparison:
  
  ✓ Keck with AO: \(V \sim 12-14, K \sim 23-25\) (Strehl dependent, point source, 1hr)
  
  ✓ KI: \(K \sim 9-10\) (no phase referencing)

So, what can be done? Example: Measure the inner radius of a YSO disk

Assume a simple morphology

Use complementary data

Fit an interesting parameter (e.g. size) to the visibility data

\[
\begin{align*}
\text{Ring D} &= 2.52 \pm 0.3 \text{mas} \\
\epsilon &= 0.29 \pm 0.05 \text{ AU}
\end{align*}
\]
First generation modern interferometers had: \( B \sim 10s - 100s \) m, \( D \sim 10 - 50 \) cm. Mainly contributed single-baseline, single-wavelength (vis, NIR) measurements of galactic objects (stars of many kinds and their dusty & molecular environment).
More Observables & Advanced Modes

- Spectral information: $V_\lambda$, $\phi_\lambda$
  - Probe different emission mechanisms, size scales, etc
    (e.g. thermal emission from different regions in YSO disks)

- Astrometry:
  - Analyze the fringe positions instead of their amplitudes
    (e.g. astrometric planet detection)

- Differential Phase:
  - Color dependent center of light shift
    (e.g. cool planet near hot star).

- Image complex morphologies via CP measurements and dense uv coverage
  (e.g. directly image terrestrial planet regions in YSO disks).

- Nulling:
  - High contrast detections (e.g. planet next to bright star)
  - A Terrestrial Planet Finder candidate technique.
KI (Keck Interferometer)

- Interferometry with the two D=10m Keck telescopes.
- B=85m baseline.
- Located atop Mauna-Kea, Hawaii.
- A NASA project to perform science in support of Navigator Program missions (exo-planet finding & characterization).
- Observing available to the community through NASA, Caltech, UC, UH, NOAO TACs.

VLTI (Very Large Telescope Interferometer)

- Interferometry with the 4 VLT Unit telescopes D=8.2m.
- Plus an array of 4 re-locatable D=1.8m outrigger telescopes.
- B=8m - 200m maximum baseline.
- Located atop Cerro Paranal, Chile.
- An ESO facility open to investigations in all areas of astrophysics.

Both obtained first fringes in 2001
KI Modes

- High sensitivity visibility amplitude measurements ($V^2$ mode)
  - In the near infrared (H[1.65um]&K[2.1um]).
  - In operations since June 2004.

- Nulling interferometry in N-band (8 - 12 um)
  - Suppress light from central star to reveal faint extended emission around it.
  - Key Science: characterize exo-zodi emission around Sun-like stars to inform TPF mission design.
  - Currently in commissioning & shared-risk science (expected to go operational in May 2007).

- Differential Phase
  - Multi-color fringe phase measurements between 2-5 µm.
  - Key Science: direct Hot Jupiter detection (orbital params & masses).
  - Currently in suspended development in favor of nulling mode.
KI Nulling

- Characterize exo-zodiacal emission from nearby sun-like stars. Goal: 10 SSZ (1 SSZ=x300 earth signal at 10um!)
- 2 problems:
  - Bright star.
  - Bright MIR background.
- Approach: 4 aperture architecture.
  - Null the star on long baseline dark fringe.
  - Modulate the leakage using broad short baseline fringes (interferometric chopping)
- Current performance: 100:1 nulls, 0.003 error in normalized & calibrated leakage. Need (0.0006,0.0018) for (10,30) SSZ detection.
- Now available for shared risk observations.
  - Serabyn E. et al. 2004, SPIE, 5491, 806
# Current VLTI Instruments

<table>
<thead>
<tr>
<th>Spectral Bands</th>
<th>Number of Telescopes</th>
<th>Spectral Resolution</th>
<th>Limiting Magnitude (with UTs)</th>
<th>Measurement Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMBER J,H,K (1.0-2.4 um)</td>
<td>3</td>
<td>35, 1500, 12000</td>
<td>~ 7, 4, 1.5</td>
<td>V(λ), CP (λ), DP</td>
</tr>
<tr>
<td>MIDI N (8 - 13 um)</td>
<td>2</td>
<td>30, 230</td>
<td>4, 2.8 (1 Jy, 3 Jy @ 12um)</td>
<td>V(λ), DP</td>
</tr>
</tbody>
</table>

- First light instrument (VINCI) now decommissioned.
- Note: sensitivity numbers are conservative, and without fringe tracking (FINITO).
- AMBER: Petrov R. et al. 2003, SPIE 4838, 924
Science Highlights

- A large variety of astrophysics topics:
  - First extra-galactic observations! (AGNs).
  - Pre-planetary disks around young stars of all types.
  - Pre-main sequence stellar masses.
  - Low mass stars diameters.
  - Gravity & limb darkening.
  - Rotating Be stars, Cepheid pulsations & distances.
  - Evolved star atmospheres, Mira pulsations.
  - Symbiotic systems and PN.
  - WR stars.
  - Asteroseismology.
  - Novae …

- Many refereed science papers (8 KI, 40 VLTI; scales with amount of sky time).

- Large amount of public data available:
  - http://msc.caltech.edu/
Active Galactic Nuclei

- NGC4151 (Seyfert 1), KI.
  - Swain et al. 2003
- NGC1068 (Seyfert 2), VLTI VINCI & MIDI.
  - A few more objects in the pipeline.
- NGC4151 NIR emission is very compact (92% flux in <0.06 pc).
- NGC1068 NIR emission compact, but less (50% flux in 0.4 pc).
- MIDI 10um sizes also require a compact (0.7pc) hot component embedded in a warm larger one (2-3pc).
- MIDI correlated flux spectra require non-standard dust, as reported in other S2 galaxies.

- These results are consistent with the unified model of AGNs (more fractional flux coming from surrounding material at larger spatial scales when central engine is partially obscured -- S2 types).

Putative central structures (accretion disk, dust torus ...) too small (~1pc) to be resolved by even the largest telescopes.
Disks around Young Stars

KI: measuring the location of the dust disk inner edge

VLTI/MIDI: revealing radial gradients in disk mineralogy

Direct heating of inner dust disk

"Standard" Disk Model – oblique disk heating

Reviewed in Millan-Gabet et al. Protostars and Planets V
Probing Disk/Wind in Hot Young Stars

Line interferometry with AMBER:

Malbet, Benisty et al. 2005
Future Developments

**KI**

- Sensitivity improvements.
- Spectral resolution ($K'$ grism, 42 channels).
  - e.g. probes gas YSO disk.
- Resume DP development.
- New visibility mode at L-band (3um).
  - e.g. probe new disk regions.
- Dual star mode phase referencing (w. LGS-AO) for & μ-arcsec astrometry of faint objects (funded NSF proposal).
  - The galactic black hole.
  - Exo-planets.

**VLTI**

- Install dual star phase referencing facility (PRIMA).
- 2nd generation instruments:
  - VSI:
    - AMBER successor
    - 4-6 beams
    - 1 - 2.5 um
  - MATISSE:
    - MIDI successor
    - 4 beams
    - 3 - 20 um
  - GRAVITY:
    - Narrow-angle (10s umas) astrometry.
    - Design driven by galactic BH studies.
Conclusions

- New-generation large optical interferometers have begun to deliver their scientific potential by exploiting increased sensitivity & spectral resolution.
- An explosion of new results in many areas is to be expected as the full array of observables, imaging capabilities and high contrast modes are also exploited.
- Other new ground based facilities: CHARA, LBTI, MRO project ... Also, community considering merit of an “Optical VLA” (NOAO Workshop in Tucson, November 2006).
- They also provide invaluable experience for the development and exploitation of space interferometers (e.g. SIM, TPF-I/Darwin):
  - Preparatory science.
  - Learning to do μas astrometry.
  - Learning to do Nulling.
  - Learning to address many technological hurdles.
An International TPF/Darwin Workshop:
*Star-Planet Interactions and Implications For Habitability*
November 8-11, 2006
Pasadena, CA
Held Jointly With the “Cools Stars XIV” Conference

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**Topics will include:**

- TPF-C & TPF-I/Darwin Overview and Mission Status
- Stellar Properties and the Habitability of Planets
- Planets Around Low Mass Stars
- Atmospheric Signatures of Rocky and Gas Giant Planets
- General Astrophysics with TPF-C/TPF-I/Darwin
- Key Technologies: Starlight Rejection, Large Telescopes and Formation Flying

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