Some Astronomical Applications of High accuracy Stellar Interferometry

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One of Dave Buscher’s 4 bullets for major technical upgrades, but for what science?

Assuming enough baselines, angular resolution and sensitivity, what would then be the contrast threshold (if any) for “great science”? 

- Direct detection and Mid-IR spectra of exo-Earths
- Performance Threshold ??
- Debris disks at few solar zodis level – Hot Jupiters – Detailed images of PP disks
- Debris disks at 100 solar zodis level – Exoplanets caught at formation
- Asymmetries (AGB stars, fast rotators) – Pulsation (AGB stars, Cepheids)
- Approximate size measurements (stars, YSO disks, AGN regions)
High Accuracy Phase Measurements, essentially Closure Phase (also CP nulling, DP, DCP, and other differential phase observables, but not discussed here)

- Can not detect centrally symmetric structures (clumps and companions OK, but misses the main component of disks)
High Contrast: Amplitude

- High Accuracy Visibility Amplitude Measurements

  - Long baseline interferometry at K band: FLUOR on IOTA and then on CHARA


  - Single telescope “dual aperture masking” nulling: detection limits around \( 1000:1 \) at K band

  - Near future at CHARA and at LBTI

  - Can detect centrally symmetric structures but cannot disentangle between disks and point sources without ancillary data (CP data, disk inclination...)

  - One possible route for high contrast is to keep system visibility very close to 1 \( \Rightarrow \) very deep nulling, working great in the lab, even broad-band
In a perfect world

History of interferometric contrast achieved in the lab world-wide
INTERFEROMETRIC OBSERVATIONS OF LATE TYPE STARS IOTA (FLUOR + TISIS: 1998-2005)

- 1% ish Visibility accuracies – Very low spectral resolution

\[
\begin{align*}
R_\star &= 10.94 \pm 0.85 \text{ mas} \\
T_\star &= 3856 \pm 119 \text{ K} \\
R_{\text{layer}} &= 25.00 \pm 0.17 \text{ mas} \\
T_{\text{layer}} &= 1598 \pm 24 \text{ K}
\end{align*}
\]

Phase K: 0.79
Phase L: 0.64

R Leo
November 2000 - November 2001

\[
\begin{align*}
\tau_{2.03 \mu m} &= 1.19 \pm 0.01 \\
\tau_{2.15 \mu m} &= 0.51 \pm 0.01 \\
\tau_{2.22 \mu m} &= 0.33 \pm 0.01 \\
\tau_{2.39 \mu m} &= 1.37 \pm 0.01 \\
\tau_{L} &= 0.63 \pm 0.01
\end{align*}
\]
**Cepheids Observations** *(Merand et al. 2005 A&A)*

CHARA long baseline + FLUOR visibility accuracy

Baade – Wesselink equation:

\[ \theta(T) - \theta(0) = -2 \frac{P}{d} \int_0^T \left( V_{\text{rad.}}(t) - V_\gamma \right) dt \]

δ Cep: known distance d, measured diameter pulsation and radial velocity

→ p factor = 1.27 ± 0.06 → calibrates Cepheids P – (absolute) L relation
CHARA /FLUOR HOT DEBRIS DISKS OBSERVATIONS (ABSIL ET AL. 2013, A&A)

<table>
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<tr>
<th>Name</th>
<th>$f_{CSF}$ (%)</th>
<th>$r^2$ (%)</th>
<th>$\chi^2$</th>
<th>$\chi^*_r$</th>
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### Graphs

- **K-band excess frequency**
  - A stars: 50%
  - F stars: 21%
  - GK stars: 14%

- **Reservoir analysis**
  - 29% Outer reservoir
  - 43% No outer reservoir
CHARA /FLUOR HOT DEBRIS DISKS OBSERVATIONS:
EXTENSION TILL 2016 (PARTIALLY FUNDED THROUGH NASA OSS GRANT)

• Expand current FLUOR survey of 42 MS stars to ~100 stars, with sensitivity to (~2X) fainter exozodi emission

• Statistical analysis of hot dust phenomenon, studying dependency on basic stellar parameters such as the existence of cold dust (MIR /FIR excess), stellar spectral type and age

• Look for correlation of the excess with the presence of massive planets previously detected by RV or transit studies.

• Study the short term evolution of the detected excess,

• Constrain the morphology of these hot debris disks, (different baselines)

• Develop new models and numerical simulations of the dynamical evolution of small hot dust grains, including the effect of gas/dust coupling close to the dust sublimation radius

• Study the wavelength dependence & nature of the excess via:
  - spectrally resolved observations in the Kband (improved FLUOR will have 8 channels)
  - complementary high contrast high resolution observations w/ other instruments (MIRC/NIRC/Palomar / LBTI)
### Results from KIN exo-zodi surveys of 41 nearby single MS stars (Mennesson & Millan-Gabet 2013)

#### Star | Spectral Type | 8-9 µm xs | 8-9 µm xs uncertainty | snr8-9 | 8-13 µm xs | 8-13 µm xs uncertainty | snr8-13 | Detected Far IR Excess | Detected NIR Excess
--- | --- | --- | --- | --- | --- | --- | --- | --- | ---
107_psc | K1V | 0.0020 | 0.0030 | 0.67 | 0.0083 | 0.0068 | 1.23 | N | N
1_ori | F6V | 0.0030 | 0.0021 | 1.41 | 0.0017 | 0.0034 | 0.5 | N | N
47_uma | G1V | 0.0014 | 0.0028 | 0.5 | -0.0018 | 0.0053 | -0.34 | N | N
70_oph | K5V | 0.0012 | 0.0022 | 0.56 | -0.0011 | 0.0028 | -0.39 | N | N
HFL4203 | M2V | -0.0004 | 0.0023 | -0.16 | -0.0026 | 0.0052 | -0.5 | N | N
betcom | G0V | 0.0058 | 0.0048 | 1.2 | 0.0020 | 0.0060 | 0.5 | N | N
bet_vir | FPV | -0.0021 | 0.0030 | -0.7 | -0.0004 | 0.0033 | -0.11 | N | N
cas1_ori | GDV | -0.0009 | 0.0027 | -0.34 | -0.0018 | 0.0036 | -0.23 | N | N
eta_crv | F2V | 0.0270 | 0.0032 | 8.35 | 0.0443 | 0.0051 | 8.69 | Y | N
gam_leo | F6V | -0.0030 | 0.0018 | -1.67 | -0.0011 | 0.0024 | -0.46 | N | N
gamma_oph | A0V | 0.0087 | 0.0028 | 3.08 | 0.0113 | 0.0051 | 2.22 | Y | N
gamma_ser | F8V | -0.0044 | 0.0023 | -1.87 | -0.0033 | 0.0037 | -0.9 | N | N
eota_pisc | FPV | -0.0045 | 0.0021 | -1.82 | -0.0038 | 0.0037 | -0.07 | N | N
kap1_cet | F7V | 0.0024 | 0.0030 | 0.79 | 0.0082 | 0.0048 | 1.71 | N | N
kap1_cet | F7V | -0.0036 | 0.0036 | -0.98 | -0.0085 | 0.0061 | -1.39 | N | N
lam_aur | K3V | 0.0035 | 0.0025 | 1.39 | -0.0013 | 0.0049 | -0.23 | N | N
lam_aur | G1V | -0.0062 | 0.0030 | 2.06 | 0.0056 | 0.0062 | 0.91 | N | N
nsv_4765 | K3V | -0.0046 | 0.0030 | -1.53 | -0.0031 | 0.0063 | -0.5 | N | N
tau_bod | F6V | 0.0031 | 0.0021 | 1.46 | 0.0032 | 0.0045 | 0.47 | N | N
theta_lei | FPV | -0.0016 | 0.0028 | -0.56 | 0.0004 | 0.0045 | 0.98 | N | N
ups_and | F9V | -0.0011 | 0.0031 | -0.34 | -0.0008 | 0.0052 | -0.16 | N | N
61_vir | G7V | 0.0051 | 0.0030 | 1.7 | 0.0046 | 0.0086 | 0.69 | N | N
69_uma | F9V | -0.0039 | 0.0030 | -1.31 | -0.0002 | 0.0062 | -0.03 | N | N
70_vir | G2V | 0.0040 | 0.0022 | 1.84 | 0.0056 | 0.0035 | 1.6 | N | N
beta_leo | A3V | 0.0056 | 0.0014 | 3.96 | 0.0042 | 0.0019 | 2.31 | Y | Y
alp_psa | A4V | 0.0015 | 0.0014 | 1.05 | 0.0037 | 0.0016 | 2.34 | Y | Y
beta_cap | F2V | 0.0021 | 0.0020 | 1.03 | 0.0017 | 0.0022 | 0.77 | N | N
beta_uma | A2IV | 0.0071 | 0.0018 | 4.02 | 0.0054 | 0.0025 | 2.54 | N | N
delta_uma | A2IV | 0.0065 | 0.0041 | 1.59 | 0.0089 | 0.0054 | 1.58 | N | N
delta_uma | K2V | 0.0025 | 0.0012 | 2.16 | 0.0018 | 0.0014 | 1.26 | Y | Y
etta_leo | F2V | -0.0006 | 0.0017 | -0.12 | -0.0039 | 0.0028 | -1.37 | N | N
nets_aep | A2IV | 0.0059 | 0.0018 | 3.3 | 0.0095 | 0.0031 | 3.12 | Y | Y
tau_ceti | G9V | -0.0011 | 0.0021 | -0.53 | -0.0008 | 0.0033 | -0.25 | Y | Y
vega | A0V | 0.0021 | 0.0009 | 2.3 | 0.0022 | 0.0010 | 2.13 | Y | Y
eta_cas_A | G3 | 0.0031 | 0.0020 | 1.55 | 0.0033 | 0.0027 | 1.21 | N | Y
alp_cep | A0V | 0.0003 | 0.0010 | 0.17 | 0.0009 | 0.0027 | 0.34 | N | Y
set_alp | A0V | 0.0016 | 0.0004 | 0.82 | 0.0018 | 0.0050 | 0.36 | N | Y
lam_germ | A3V | -0.0030 | 0.0030 | -1 | -0.0041 | 0.0061 | -0.67 | N | Y
10_Tau | F8V | 0.0076 | 0.0041 | 1.84 | 0.0024 | 0.0088 | 0.28 | N | Y
alr_424 | A7V | 0.0023 | 0.0014 | 1.5 | 0.0038 | 0.0015 | 2.55 | N | Y
kappa_crb | K1V | 0.0031 | 0.0044 | 0.8 | 0.0064 | 0.0059 | 1.68 | Y | N

- **Red:** detected KIN excess
- **Blue:** likely KIN excess

- Extends RMG 2011 analysis paper (full N-band, 25 → 41 stars)
- Strong spectral dependence of detected excess (age effect?)
- Strong correlation with far IR excess (cold dust)
- Only 2 (to 4) of the 12 NIR excess stars show a KIN MIR excess
- Best 1-σ excess detection limit is 0.1% (typical is 0.2-0.3%)
INDIVIDUAL STAR RESULTS
Radiative modeling of multi-wavelength interferometric data (GrateR, Augereau, Lebreton) suggests two distinct dust populations:

- (1) a population of very small (0.01 to 0.5µm), hence unbound, hot dust grains confined in a narrow region (~0.1 – 0.3 AU) at the sublimation rim of carbonaceous material (tip of the iceberg)
- (2) a population of bound warm grains at ~2AU that is protected from sublimation and has a higher mass despite its fainter flux level.
**KIN surveys Statistical results**

- All histograms are heavily skewed towards positive detections.
- Zodi level and excess significance distributions show 8+ stars with a MIR excess detected by the KIN.
- Will feed into ~10x higher accuracy LBTI survey.
HIGH CONTRAST INTERFEROMETRIC OBSERVATIONS WITH THE PALOMAR FIBER NULLER (PFN)
PFN Optical Set-up: a mini nulling interferometer

- Pupil Mask defines two 1.5 x 3m elliptical apertures 3.2m apart
- K mirror provides baseline rotation
- Palomar AO system stabilizes OPD (~200nm rms) and individual beam intensities
- Chopper wheel measuring interferometric, dark and individual beams every 200ms
- Both beams injected into a common IR SM fiber
PFN observing sequence: acquisition at a given baseline orientation

2ms sampling + beam chopping at 5-10 Hz

Null Sequence based on chopped data
**Visibility Self Calibration principle**

Fringe tracked data recorded close to central dark fringe

Calibration Signals: Dark, I₁, I₂

Single-mode monochromatic assumption for the interferometric signal:

\[ I(t) = I₁(t) + I₂(t) + 2|V| \sqrt{I₁(t)I₂(t)} \cos(\phi(t) + \phi_V) + D(t) \]
Null/Visibility Self Calibration Requirements

- Needs single-mode fringe tracked data ($\sim \lambda/10$ rms) sampled faster than coherence time
- Needs some photometric and background measurements close in time (within 1 mn)
- Needs Dispersed data if long baselines used [unless longitudinal dispersion effects are negligible e.g. LBTI common mount, single telescope NRM, vacuum delay lines]

- Deconvolution of instrumental effects (piston and intensity mismatch) making use of whole dataset
- Can work with average nulls as bad as 10% and fluctuating by the same amount, and still measure underlying astro nulls < 0.001 with a few 10^-4 accuracy
- Works as well on resolved objects, measuring accurate visibilities (tested on archival KI FT data)
PFN Visibility Measurement Accuracy: \( \alpha \) Boo

If \( N(t) = N_{\text{ast}} + \sum \text{quadratic terms} \), the average measured null (or visibility) is \textit{NOT} the best observable!! The analysis of the distribution provides a much better and more robust estimator (Mennesson et al. 2011b, 2013 in prep: KI data).

\[
N_{\text{ast}} = 0.0130 \pm 0.0005 \\
<N> = 0.065
\]

\[
N_{\text{stro}} = 0.0132 \pm 0.0003 \\
i.e. \text{Visibility} = 0.9739 \pm 0.0006
\]

Very different instrumental conditions, but same visibility measured within a few \( 10^{-4} \) (June 2009 Engineering run data)
HIGH CONTRAST OBSERVATIONS OF DEBRIS DISKS USING DIFFERENT INSTRUMENTS: VEGA (PFN+MMT+KIN+CHARA)

PFN measurements + KIN & MMT constraints:

→ NIR Vega excess seen by CHARA/FLUOR and IOTA/IONIC (Defrere et al. 2011) must come from inside of 0.15 AU
→ Not seen by KIN → very hot small grains

Similar to Mennesson et al. 2011, ApJ, 736, 14 but revised with new PFN data from 2012 (Vega’s excess null = $3 \times 10^{-4}$ +/- $3 \times 10^{-4}$, submitted to JAI as part of 2013 CHARA-NPOI conf proceedings)

[ PFN observations 2011-2013: similar results on 6 FLUOR excess sources → Any NIR excess would have to come from very close-in, close to the sublimation radius ]
PFN OBSERVATIONS OF AB Aur

Jonas Kuhn, in prep
**Instrumental Limitations to High Accuracy Visibility Amplitude Measurements**

- Dispersion Effects: Atmospheric Refraction across the band (oscillation of observed vis/null if longitudinal dispersion not actively corrected) → ADC needed or high spectral R.
- Dispersion effects: optical set-up (Palomar 200” AO dichroic !)
- Finite integration time -> residual phase jitter (depends on baseline length)
- Need for short integrations wrt $\tau_0$ (not an issue for CP ?)
- Polarization mismatch evolution vs time

Visibility oscillation period goes as $1/ (B \cdot \frac{dn_{air}}{d\lambda})$
Visibility oscillation amplitude goes as $B^2 \Delta\lambda^2$
HIGH CONTRAST INTERFEROMETRIC STUDIES: FUTURE

- **Palomar FN** (K=5 → K=7, contrast > $10^3$ between 30 and 200 mas)
  - Programs: planetary formation (the first 10 Myr, e.g. AB Aur results and a few CHARA/FLUOR hot debris disks → ends in 2014. Demonstrator for $10^4$:1 contrast in the NIR.

- **CHARA/FLUOR**: Extension of NIR hot disk survey
  - 42 → 100 stars by 2016, K<5, 0.1% V accuracy (using VSC method on fringe tracked dispersed data)
  - Objectives: radiative transfer modeling and better understanding of dynamical aspects (how do such small grains escape radiative blow-out over long timescales?)

- **CHARA/MIRC and VLTI/PIONIER**
  - Any way /need to further improve CP accuracy which is already the best in the world?

- **VLTI: MATISSE (L,M,N)**
  - Planetary formation: Imaging of young stars and debris disks. Any possibility / need to improve currently planned CP and visibility accuracies? (dynamic range not a priority at the moment)

- **LBTI Nuller Survey (N)**
  - Goal: survey 60 nearby MS stars down to 3 to 30 zodis level (2013-2016) ..................
  - Measure background down to < 1ppm (lower than keck, multi-pixel array → 2ppm already
  - Apply VSC method to measure nulls much deeper than mean null level and rms fluctuations

- **New Ideas: CP +Nulling? (John, Mike, Sylvestre...)**