Observations of Exozodiacal Dust with the Keck Interferometer Nuller

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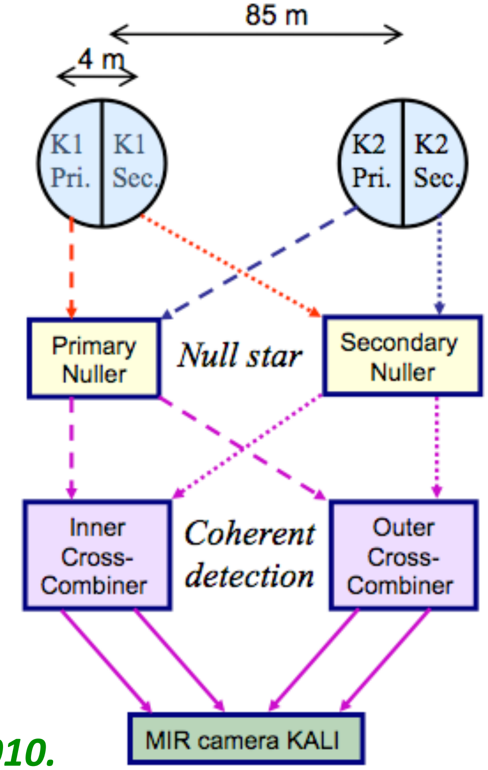
Why study debris disks?

- **Time scales for debris disk evolution may help understand terrestrial planet formation (see e.g. Wyatt 2008).**
- **Use disk structure to infer the presence of unseen planets (e.g. Wolf 2007, Stark & Kuchner 2008). Some have now been seen (HR8799 - Marois 2008, Fomalhaut - Kalas 2008).**
- **Knowledge of exozodi levels and structure is needed in order to properly design future terrestrial planet finding/imaging missions (see e.g. Exoplanet Community Report 2009, Exoplanet Task Force report Lunine 2008, Astro2010):**
  - **True for both vis coronographs and IR interferometer concepts.**
  - **Knowledge of the exozodi levels for all candidate stars would allow a greatly optimized instrument and strategy design.**
  - **Another problem: distinguish planets from disk blobs.**
- **Note: imaged Kuiper disks show rich morphology variety**

➔ not a good idea to extrapolate to exozodi regions …

The Keck Interferometer Nuller – Key Aspects

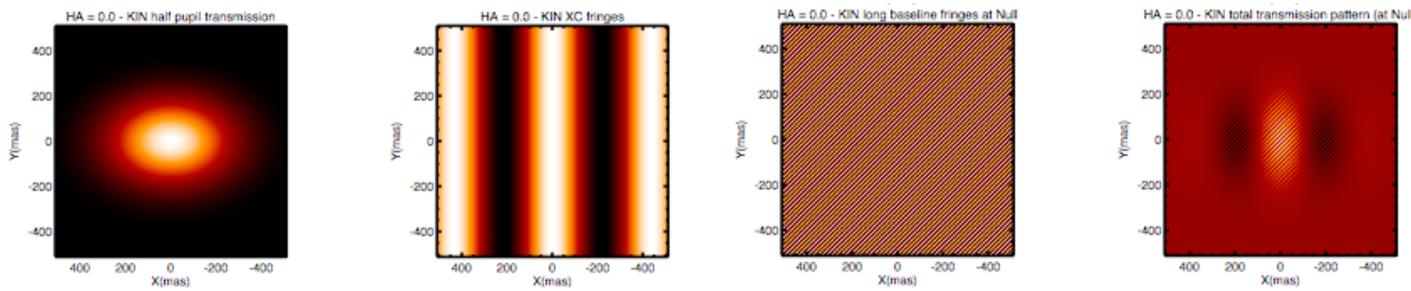
- **Spectral band: 8 – 13 µm, λeff=8.5 µm.**
- **Double-nuller architecture:**
  - **In order to deal with thermal background.**
- **Long baseline fringes**
  - **Accommodate large DR between star and surrounding dust.**
  - **Provide sensitivity to inner dust: 0.1 AU (at 10pc).**
- **Short baseline fringes:**
  - **Allow detection in presence of large IR background.**
  - **Also, provides accurate flux normalization.**
- **Results in well calibrated measurement (e.g. sub-% accuracy in equivalent fringe visibility, much better than standard Michelson MIR interferometry).**
- **FOV: from 0.1 AU to ~4 AU at 10 pc**
  (limited by half-aperture PSF and short baseline fringes).
- **Limiting flux: 1.5 Jy at N band.**



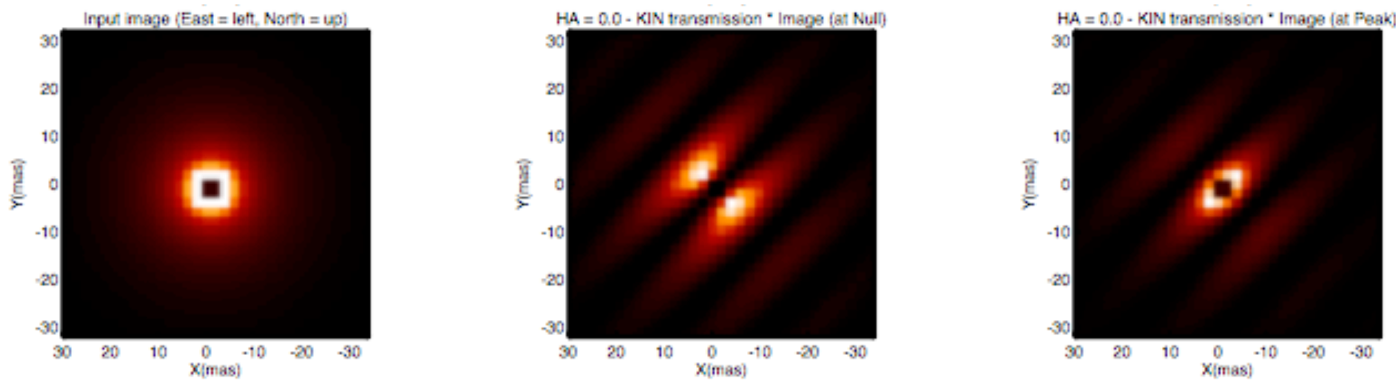
Instrument details: Colavita 2009, 2010.

What the KI Nuller Measures

Fringe patterns on the sky:



zoom:
(zodi with central star removed)



Measured normalized "Leak":

$$L = \frac{F^{transmitted}_{at\,null}}{F^{transmitted}_{at\,peak}} \begin{cases} = 0 \; if \;\; no\ zodi\ dust \\ > 0 \; otherwise \end{cases}$$

Typical accuracy:

$$\sigma_L = 0.003 \; (0.3\%)$$

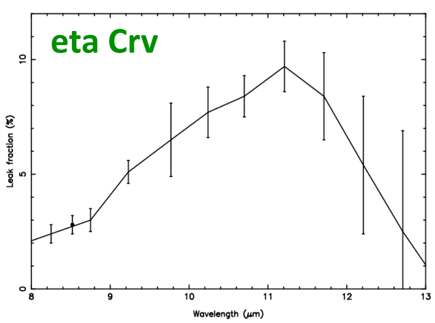
Convert to Number of Zodis

$$(measured\ Leak - stellar\ Leak) \approx \frac{\iint Zodi\_Brightness * (KINPattern)null}{\iint Star\_Brightness * (KINPattern)peak}$$

- **Compute and subtract stellar leak from the data (introduces small ~10^{-4} error, compared w. larger uncertainty in calibrating stellar spectrum in spectro-photometric techniques).**
- **Use ZODIPIC (Kuchner, GSFC) to generate an image of an analog of the solar system zodi around each target, for a given disk inclination and P.A.**
- **Scale the number of zodis until the predicted leak matches the measured net leak.**
- **This must be done for *each individual observation*, because the conversion to nzodis depends on the H.A.-dependent KIN fringe pattern (projected baseline length & orientation).**
- **Average observations and clusters in "zodi space", propagating formal and external errors.**
- **Repeat for range of dust disk orientations {inc,PA}. The resulting variability is taken as an additional uncertainty (small).**

Results: Individual Stars

- **25 stars observed**
  - **2 "high dust" ("Kuiper dust": η Crv, γ Oph).**
  - **23 no known dust.**
- **1 clear detection:**
  - **η Crv: z=1250 ± 260**
  - **Spectrum has adequate S/N, Si feature observed => follow up work.**
- **2 possible detections:**
  - **γ Oph: z=200 ± 80**
  - **α Aql: z=600 ± 200**
- **22 non-detections: derive exozodi upper limits.**



Mostly FGK stars

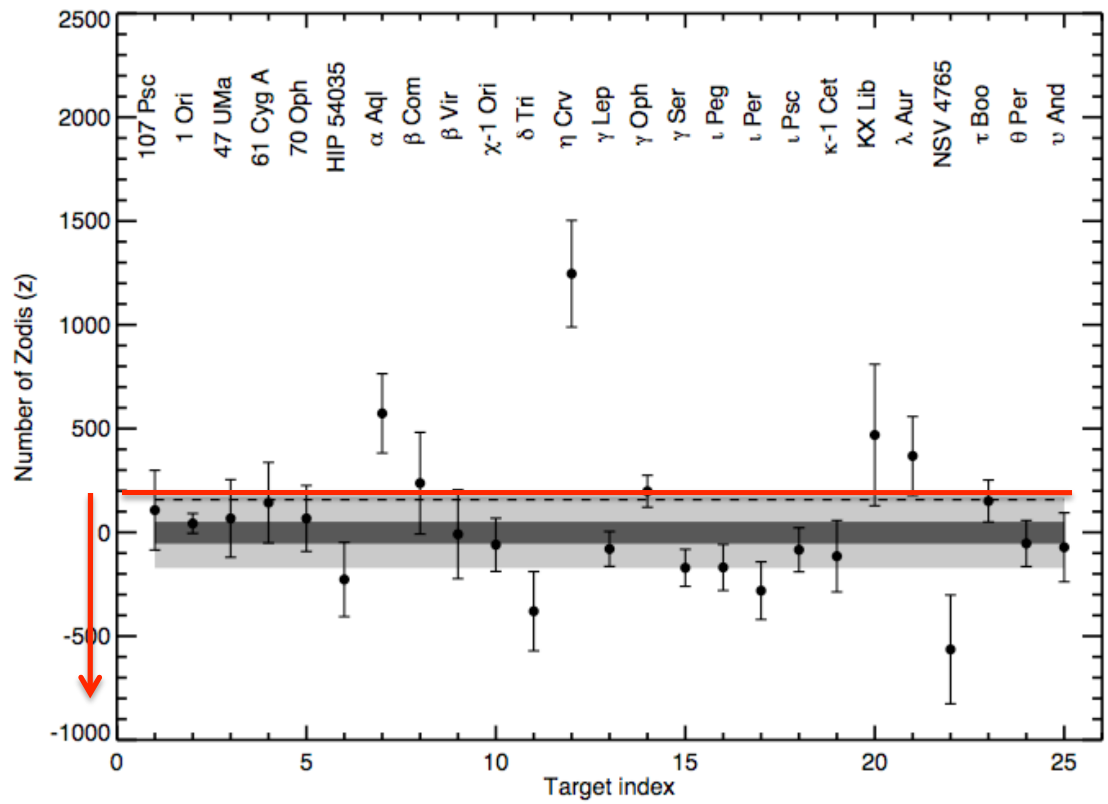
Table 5
Average Number of Zodis for Each Target

Name	$z \pm \sigma_z$	$\chi = \frac{z}{\sigma_z}$	3σ Upper Limits
Detections			
η Crv	1246 ± 257	4.8	...
Possible detections			
γ Oph	198 ± 77	2.6	429
α Aql	573 ± 191	3.0	1146
Non-detections			
107 Psc	107 ± 192	0.6	683
1 Ori	43 ± 48	0.9	187
47 UMa	67 ± 187	0.4	628
61 Cyg A	143 ± 194	0.7	725
70 Oph	67 ± 159	0.4	544
HIP 54035	−227 ± 179	−1.3	537
β Com	237 ± 245	1.0	972
β Vir	−9 ± 214	−0.0	642
χ-1 Ori	−60 ± 128	−0.5	384
δ Tri	−380 ± 191	−2.0	573
γ Lep	−80 ± 84	−1.0	252
γ Ser	−171 ± 89	−1.9	267
ι Peg	−169 ± 111	−1.5	333
ι Per	−281 ± 139	−2.0	417
ι Psc	−84 ± 106	−0.8	318
κ-1 Cet	−115 ± 172	−0.7	516
KX Lib	469 ± 341	1.4	1492
λ Aur	368 ± 190	1.9	938
NSV 4765	−564 ± 262	−2.2	786
τ Boo	151 ± 101	1.5	454
θ Per	−54 ± 111	−0.5	333
υ And	−72 ± 166	−0.4	498
		Average	567

Average 1σ error
160 zodis

Results: Population

- 23 stars not previously known to have zodi dust.
- If these stars represent a population from the point of view of warm exozodi emission; and if the measurements are uncorrelated:
- mean: $z = +2 \pm 50$.
- Mean exozodi level for the class: < 150 zodi (3σ).



Current knowledge on MS stars zodi level

- **From Spitzer observations of nearby MS stars (e.g. Trilling et al. 2008, Lawler et al. 2009)**
  - **$16.4^{+2.8}_{-2.9}$ % have a detected 70 μm excess (out of 225 sun-like FG stars): rather KB than zodi analog**
  - **11.8 +/- 2.4 % have a 32 μm excess (out of 203 FGKM stars, using 3σ excess= 6% ~ 100 zodis)**
  - **$4.2^{+2.0}_{-1.1}$ % have a 24 μm excess (out of 213 FG stars, 3σ excess =10%)**
  - **1+/- 0.7 % have a 10 μm excess (out of 203 FGKM MS stars, 3σ excess= 3% ~ 1000 zodis)**
  - **Excess rates statistically indistinguishable between A, F, G and K stars**
- **From 10 μm KIN observations of 23 nearby AFGKM stars with no Spitzer excess (this work)**
  - **1 star shows a ~1% excess within 2 AU, at 3σ = 600 zodis.**
  - Suggests 99% of such stars have zodi levels < 150 zodis
- **From NIR interferometric observations of 40 MS AFGK stars (Absil et al.)**
  - **10 stars show an excess at the ~1% level, (origin remains unclear)**
  - **Excess rate seems to decrease vs spectral type (small statistics)**
  - **Nine of them observed by MIR nulling interferometry (KIN, MMT): only 1 shows significant 10 micron excess emission imputable to a debris disk (e.g. Stock et al. 2010)**

Conclusions & Future work

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EXOZODIACAL DUST LEVELS FOR NEARBY MAIN-SEQUENCE STARS: A SURVEY WITH THE KECK INTERFEROMETER NULLER

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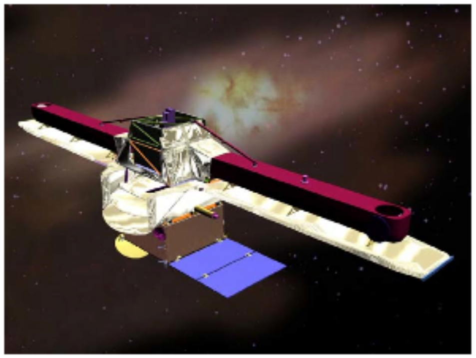
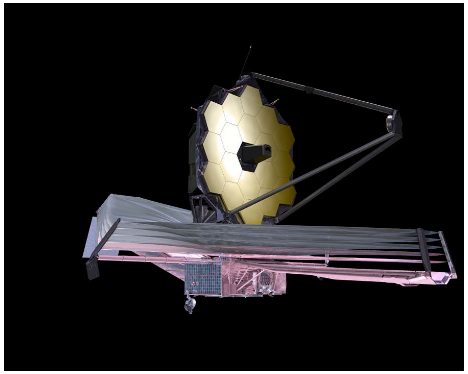
- **Encouraging results for future direct exoplanet imaging missions.**
- **But limits measured still may imply higher levels than can be tolerated.**
- **Need 10-100x (?) better measurements.**



- **LBTI goal: 80 stars down to 10 zodis (1σ).**
- **Do we need to know about 1-zodi levels?**
- **A dedicated sub-orbital or space mission?**



- **Still need to solve the problem of dealing with disk inhomogeneities.**
  - **Direct characterization of morphologies, or address with appropriate observing mitigation strategy?**