A near-infrared interferometric survey for bright exozodiacal disks

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Dust in planetary systems

- We all live in a debris disk!
  - 2nd generation dust (asteroids, comets)
- Dust is luminous (**much** more than planets)
- Dust is expected in any planetary system

Kuiper belt: 40 K, 50 AU

Zodiacal disk: 300 K, 1 AU
Dust not uniformly distributed

Golimowski et al. 2006; Greaves et al. 2005; Schneider et al. 2005; Holland et al. 1998; Stark & Kuchner 2008; Wyatt et al. 2006

Observations

Simulations

Earth at 1 AU
Inner vs. outer debris disk

- **T ~ 40 K**
  - Prominent far-IR excess
  - Easy to resolve (>1”)

- **T > 300 K**
  - Small near/mid-IR excess
  - Difficult to resolve (< 0.1”)

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<tr>
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<th>flux</th>
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The exozodi problem

- «A mote of dust suspended in a sunbeam»

Picture taken by Voyager 1 in 1990 (40 AU from Earth)
Mid-infrared spectro-photometry

- Spitzer/IRS (5-34 µm)
- Spitzer/MIPS (24 µm)
- Sensitivity
  - ~1000 zodi (8-12 µm)
- Statistics
  - ~1% warm excess
- Limited by
  - Photometric accuracy
  - Model of the stellar photosphere

Beichman et al. 2006; Lisse et al. 2012
Mid-infrared imaging

- Bright exozodis resolved only in favorable cases
  - Nearby star
  - Large telescope
- Ground-based → large background
  - Sensitivity ~ 1000 zodi
- Future: JWST/MIRI, ELT/METIS
  - Down to a few zodis?
Near-IR interferometry

Principle and first results
Principle of exozodi detection

- Disk larger than $\lambda/B \rightarrow$ visibility loss
- Best detected at short baselines (~10-30m)

\[ V^2 \approx (1 - 2f) \left( \frac{2I_1(\nu b \theta / \lambda)}{\pi b \theta / \lambda} \right)^2 \]

Requires very good accuracy (~1%)
High precision interferometers

FLUOR at CHARA

IONIC at IOTA

VINCI and PIONIER at VLTI
Vega viewed by CHARA/FLUOR

Mean $\theta_{LD}$: $3.328 \pm 0.003 \pm 0.013$ mas

Disc/star: $1.26 \pm 0.2 \chi^2 = 0.069\%$

$\chi^2 = 1.18$
Morphology?

- H-band short baseline data (IOTA/IONIC)
  - No closure phase $\rightarrow$ not a point-like source
  - Dust distribution not constrained

Defrère et al. 2011
Possible sources of near-IR excess

- **Point-like source?**
  - No closure phase signal
  - RV and astrometry stable
  - Very low probability for background star

- **Stellar wind / circumstellar gas?**
  - A stars: very weak winds ($\sim 10^{-12..14} M_\odot/yr$)
  - Free-free emission: should be stronger at mid-IR
  - Ae/Be phenomenon: no evidence for H\(\alpha\) emission

- **Circumstellar dust?**
  - Thermal emission & reflected flux

- **New, unknown phenomenon?**
Radiative transfer modeling

- H- and K-band interferometry
- N-band nulling interferometry (MMT/BLINC)
- Archival near- to mid-IR spectro-photometry
Most probable dust properties

- Bayesian $\chi^2$ analysis of large parameter space
  - Grains < blowout size
  - Hot grains (> 1000 K)
  - Presence of carbons ≥ 10%
  - Distance: ~ 0.1 – 0.5 AU
  - Steep density power law: $\alpha < -3 \rightarrow$ ring?
- Mass: ~$2 \times 10^{-9}$ M$_{\text{Earth}}$
- Luminosity: ~$5 \times 10^{-4}$ L$_{\text{star}}$

Defrère et al. 2011
New view of Vega

Holland et al. 1998

Debris disk

200 AU

$3 \times 10^{-3} \, M_\oplus$

$3 \times 10^{-5} \, L_\star$

$2 \times 10^{-9} \, M_\oplus$

$5 \times 10^{-4} \, L_\star$

0.2 AU
Origin of hot dust: steady state?

- Local production?
- Connection to outer disk?
  - Poynting-Robertson drag?
  - Multiple scattering of comets?
N-body simulations for Vega

Vega: 455 Myr, 46.7 M\textsubscript{Earth}

(Vonnier12)

Fig. 12. Total outer belt mass required if scattering by a chain of equal mass planets, as shown in Fig. 9, or detailed in Table 3, is to replenish an exozodi inside of 1 AU around Vega at the required rate of $10^{-9}$ M\oplus/yr.
Origin of hot dust: transient?

- Isolated event?
  - Large collision (e.g. Earth-Moon)
  - Break-up of giant comet
- Dynamical perturbations?
  - Falling Evaporating Bodies
    - Asteroid belt disturbed by MMR with massive planet
  - Late Heavy Bombardment
    - Global rearrangement
- Statistical study may help
A near-IR survey
CHARA/FLUOR observations
Survey at CHARA/FLUOR

- Magnitude-limited sample
  - (All) northern stars with far-IR excess and K<4
  - ~ same amount of “non-dusty” stars
- Evenly spread between spectral types A, F and G-K
- Diameters predicted from surface-brightness relationships

<table>
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<tr>
<th></th>
<th>Dusty</th>
<th>Clean</th>
<th>Total</th>
<th>&lt;Kmag&gt;</th>
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<tbody>
<tr>
<td>A</td>
<td>8</td>
<td>4</td>
<td>12</td>
<td>2.4</td>
</tr>
<tr>
<td>F</td>
<td>6</td>
<td>9</td>
<td>15</td>
<td>2.7</td>
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<td>GK</td>
<td>8</td>
<td>7</td>
<td>15</td>
<td>2.7</td>
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<tr>
<td>Total</td>
<td>22</td>
<td>20</td>
<td>42</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Examples ($V^2$ vs hour angle)

**Detection, many points**

**Non-detection, few points**

**Too-good-to-believe**

**High $\chi^2$**

Absil et al., in prep
eps Cep: a faint close companion

- Wavy pattern in visibilities ($\rightarrow$ large $\chi^2$)
- Confirmed with coronagraphy
  - 330 mas separation
  - 2% flux ratio

Mawet et al. 2011
More follow-up examples

Caveat: not all excesses followed up!

tau Cet

zet Aql
Survey summary (41 stars)

- Mean sensitivity (at 1σ) = 0.3%
- $0.3 < \chi_r^2 < 3$ for most targets
- Distribution core looks ~ Gaussian
  - No target with significance < -3σ
- Detection threshold set at 3σ
  - 12 excesses out of 41 stars → ~30%

Absil et al., in prep

eps Cep
Statistical trends

Absil et al., in prep
Correlation type/cold dust/hot dust

Absil et al., in prep

Exozodi detection frequency

- A stars
- F stars
- GK stars

Cold dust:
- 38%
- 50%
- 38%

No cold dust:
- 75%
- 0%
- 0%
Correlation vs rotational velocity?

Absil et al., in prep

K-band excess vs $v \sin i$ [km s$^{-1}$]
Correlation vs age?

Absil et al., in prep
Comparison with KIN

More KIN follow-up to come...
Extending the survey
First results with VLTI/PIONIER
Enlarging the statistical sample

- New targets: Spitzer, Herschel cold disks
- Go fainter
  - Refurbished FLUOR → “JOUFLU”
  - New camera, upgraded optics
  - Expect high-precision down to K~5 (good conditions)
- Go South
  - PIONIER at VLTI
  - High-precision $V^2$ down to H~5 (good conditions)
  - Same fringe scanning principle as FLUOR
  - 6 (short) baselines at a time → huge gain in speed
Goal: no bias on inner/outer disk connection study
- One non-dusty “control” star for each dusty target
  - Same spectral type
  - Similar magnitude
  - Proximity on the sky
- No binaries, bloated stars
- Distribute evenly between A, F and G-K
- Final sample: ~100+100 stars (whole sky)
New feature: low-res spectra

- Dispersed fringes with PIONIER (soon FLUOR)
  - Flux ratio measurements across H and/or K band
  - Direct constraint on dust temperature

![Graph of flux vs. wavelength with fitted lines and chi-squared values](image)
PIONIER survey status

- A lot of time spent on TF stability analysis
  - DRS validated
  - PIONIER stability validated
  - VLTI polarization effect identified
  - $V^2$ accuracy on spec after correction
- $4 \times 3n$ awarded in 2012
  - 3 runs carried out
  - 74 stars observed
How to go deeper?

Sensitivity comparison

Detectable exozodi density [zodi]

KIN
ALADDIN
PEGASE
FKSI

K0V–05pc G5V–10pc G0V–20pc G0V–30pc

LBTI?