Data Analysis and Preliminary Results of the JouFLU Exozodi Survey

Paul D. Nuñez
Exoplanet Discovery and Science Group
Jet Propulsion Laboratory,
California Institute of Technology

Current Team:
Bertrand Mennesson (JPL), Nic Scott, Theo ten Brummelaar (GSU)
Vincent Coudé du Foresto, Olivier Absil

March 2016
Towards direct imaging in the habitable zone

Beta-Pictoris b at $\lambda = 3.5\, \mu m$

$D \approx 8\, AU, \theta_{sep} \approx 0.5''$
(Lagrange et al. 2009)

Fomalhaut b at $\lambda = 0.6\, \mu m$

$D \approx 116\, AU, \theta_{sep} \approx 15''$
(Kalas et al. 2008)
Hot Circumstellar Dust in Main Sequence Stars

- Must be understood to ensure success of future direct imaging missions
- Can be used to learn about planet formation & dynamical state
- Hot dust (K band) is detected in a 25% fraction of main sequence stars (Absil et al. 2013). 12% in H-Band (Ertel, + 2014)
- Generally a $\sim 1\%$ deficit in visibility.

Viscosity Deficit from Circumstellar Disk

![Diagram showing visibility deficit from circumstellar disk](image)
37 new stars, 14 follow-ups (See N. Scott’s talk), 4 LBTI list

Total of 79 stars: 21 with a known outer cold reservoir. Nominally 3 calibrators per target.
The FLUOR/CLASSIC pipeline offers several unbiased estimators, e.g. V_NORM, V_SQRT, V_LOGNORM.

All of the current estimators assume that the measured Visibility follows Gaussian statistics (?).

Data are not always Gauss distributed.
The Median as an unbiased estimator

For each fringe scan we measure

\[ V^2 = (\mu + N_1)^2 + N_2, \]

where \( N_1 \) and \( N_2 \) are noise sources (e.g. piston and photon noise).

- If \( N_2 = 0 \) and \( \text{Med}(N_1) = 0 \) \( \Rightarrow \sqrt{\text{Med}(V^2)} = \mu \)

- In general, \( V_{\text{median}} = \sqrt{\text{Med}(V^2)} \) has a smaller bias than other estimators

![Bias for various estimators (µ = 0.3, σ² = 0.01)](image1)

![Error for various estimators (µ = 0.3, σ² = 0.01)](image2)
Visibility Calibration

Problem: to estimate $V$ from $\mu$, raw calibrator visibilities $V_1$, and $V_2$, and calibrator expected visibilities $V_{1\text{exp}}$, $V_{2\text{exp}}$

$$V = \mu \left\{ \alpha_1 \frac{V_{1\text{exp}}}{V_1} + \alpha_2 \frac{V_{2\text{exp}}}{V_2} \right\} \frac{1}{\alpha_1 + \alpha_2}$$

Time Interpolation

$$\alpha_1(t) = \left( \frac{t_2 - t}{t_1 - t_2} \right) ; \quad \alpha_2(t) = \left( \frac{t - t_1}{t_1 - t_2} \right)$$

Weighted Mean

$$\alpha_1 = \frac{1}{\sigma_1^2} ; \quad \alpha_2 = \frac{1}{\sigma_2^2}$$
Hybrid Visibility Calibration: a compromise

Maximize prob to obtain co-Transfer function $T$ at time $t$

$$P(T, t_1) \sim \exp\left(\frac{-(T - T_1)^2}{2\sigma_1^2}\right); \quad P(T, t_2) \sim \exp\left(\frac{-(T - T_2)^2}{2\sigma_2^2}\right)$$

$$P(T, t) \sim \exp\left\{\left(\frac{t_2 - t}{t_1 - t_2}\right)\chi_1^2 + \left(\frac{t - t_1}{t_1 - t_2}\right)\chi_2^2\right\}$$

$$\Rightarrow \alpha_1(t) = \frac{1}{\sigma_1^2}\left(\frac{t_2 - t}{t_1 - t_2}\right)$$

$$\alpha_2(t) = \frac{1}{\sigma_2^2}\left(\frac{t - t_1}{t_1 - t_2}\right)$$
Testing with JouFLU data: 166 points of non-excess stars

Compared $V_{\text{median}}$ with Hybrid interpolation to other approaches: Found smaller bias and uncertainty with the new visibility estimation method.
Circumstellar Flux Excess? (6-7 new detections. Preliminary)

Red=Absil 2013 excess.  Dust  Binarity

<table>
<thead>
<tr>
<th>Name</th>
<th>ID</th>
<th>$m_k$</th>
<th>Type</th>
<th>$\chi^2_{UD}$</th>
<th>$f_{csf}/f_*$</th>
<th>$\chi^2_{csf}$</th>
<th>$N_{data}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V* del Eri</td>
<td>HD23249</td>
<td>1.13</td>
<td>K1III-IV C</td>
<td>1.40</td>
<td>1.44 ± 1.12%</td>
<td>0.10</td>
<td>2</td>
</tr>
<tr>
<td>Regulus</td>
<td>HD87901</td>
<td>1.62</td>
<td>B8Iv C</td>
<td>0.35</td>
<td>0.00 ± 0.98%</td>
<td>0.51</td>
<td>3</td>
</tr>
<tr>
<td>ksi boo</td>
<td>HD131156</td>
<td>1.97</td>
<td>G7Ve</td>
<td>1.37</td>
<td>-0.24 ± 0.46%</td>
<td>1.617</td>
<td>5</td>
</tr>
<tr>
<td>40 Eri</td>
<td>HD26965</td>
<td>2.41</td>
<td>K0.5V C</td>
<td>2.07</td>
<td>0.73 ± 0.48%</td>
<td>2.12</td>
<td>6</td>
</tr>
<tr>
<td>kap crb</td>
<td>HD142091</td>
<td>2.49</td>
<td>K0III</td>
<td>4.27</td>
<td>3.30 ± 0.6%</td>
<td>0.97</td>
<td>10</td>
</tr>
<tr>
<td>del Aql</td>
<td>HD182640</td>
<td>2.54</td>
<td>F1IV-V(n)</td>
<td>40.88</td>
<td>7.1 ± 0.40%</td>
<td>3.90</td>
<td>5</td>
</tr>
<tr>
<td>gam ser</td>
<td>HD142860</td>
<td>2.62</td>
<td>F6IV</td>
<td>4.99</td>
<td>1.70 ± 0.33%</td>
<td>2.47</td>
<td>9</td>
</tr>
<tr>
<td>iot per</td>
<td>HD19373</td>
<td>2.64</td>
<td>F9.5V C</td>
<td>1.85</td>
<td>-0.35 ± 0.27%</td>
<td>1.91</td>
<td>4</td>
</tr>
<tr>
<td>iot Pcs</td>
<td>HD222368</td>
<td>2.75</td>
<td>F7V C</td>
<td>4.61</td>
<td>1.29 ± 0.25%</td>
<td>1.46</td>
<td>8</td>
</tr>
<tr>
<td>ups and</td>
<td>HD9826</td>
<td>2.84</td>
<td>F9 V C</td>
<td>6.84</td>
<td>3.03 ± 0.49%</td>
<td>0.73</td>
<td>6</td>
</tr>
<tr>
<td>zet aql</td>
<td>HD177724</td>
<td>2.88</td>
<td>A0IV</td>
<td>2.02</td>
<td>1.22 ± 0.39%</td>
<td>0.95</td>
<td>8</td>
</tr>
<tr>
<td>eta lep</td>
<td>HD40136</td>
<td>2.90</td>
<td>F2IV C</td>
<td>1.97</td>
<td>0.75 ± 0.50%</td>
<td>1.90</td>
<td>4</td>
</tr>
<tr>
<td>HR 8832</td>
<td>HD219134</td>
<td>3.25</td>
<td>K3V C</td>
<td>0.98</td>
<td>0.37 ± 0.55%</td>
<td>1.07</td>
<td>7</td>
</tr>
<tr>
<td>lam aur</td>
<td>HD34411</td>
<td>3.27</td>
<td>G1V C</td>
<td>1.73</td>
<td>1.1 ± 0.39%</td>
<td>0.48</td>
<td>6</td>
</tr>
<tr>
<td>V* kap01 Cet</td>
<td>HD20630</td>
<td>3.27</td>
<td>G5Vv C</td>
<td>1.24</td>
<td>1.58 ± 0.94%</td>
<td>0.71</td>
<td>4</td>
</tr>
<tr>
<td>tet peg</td>
<td>HD210418</td>
<td>3.30</td>
<td>A1IVa C</td>
<td>4.95</td>
<td>2.2 ± 0.59%</td>
<td>1.79</td>
<td>4</td>
</tr>
<tr>
<td>72 oph</td>
<td>HD165777</td>
<td>3.42</td>
<td>A5V C</td>
<td>1.76</td>
<td>3.53 ± 1.28%</td>
<td>1.46</td>
<td>10</td>
</tr>
<tr>
<td>37 and</td>
<td>HD5448</td>
<td>3.49</td>
<td>A5v C</td>
<td>5.24</td>
<td>2.94 ± 0.5%</td>
<td>0.50</td>
<td>7</td>
</tr>
<tr>
<td>HR 6636</td>
<td>HD162003</td>
<td>3.50</td>
<td>F5IV-V C</td>
<td>28.02</td>
<td>7.06 ± 0.60%</td>
<td>1.67</td>
<td>5</td>
</tr>
<tr>
<td>b Aql</td>
<td>HD182572</td>
<td>3.53</td>
<td>G8IV</td>
<td>1.67</td>
<td>0.93 ± 0.71%</td>
<td>1.73</td>
<td>9</td>
</tr>
<tr>
<td>zet alf ser</td>
<td>HD164259</td>
<td>3.64</td>
<td>F2IV C</td>
<td>2.37</td>
<td>0.21 ± 0.98%</td>
<td>2.66</td>
<td>7</td>
</tr>
<tr>
<td>alf lac</td>
<td>HD213558</td>
<td>3.75</td>
<td>A1V C</td>
<td>0.53</td>
<td>-0.50 ± 1.02%</td>
<td>0.61</td>
<td>4</td>
</tr>
<tr>
<td>LTT 15404</td>
<td>HD168151</td>
<td>3.94</td>
<td>F5V C</td>
<td>2.21</td>
<td>0.08 ± 0.71%</td>
<td>2.70</td>
<td>5</td>
</tr>
<tr>
<td>gam tri</td>
<td>HD14055</td>
<td>3.95</td>
<td>A1Vnn C</td>
<td>1.48</td>
<td>-0.50 ± 1.18%</td>
<td>1.32</td>
<td>3</td>
</tr>
<tr>
<td>51 peg</td>
<td>HD217014</td>
<td>3.99</td>
<td>G2.5Iv C</td>
<td>1.00</td>
<td>-0.29 ± 0.74%</td>
<td>1.16</td>
<td>4</td>
</tr>
</tbody>
</table>
The median Kmag for the survey extension is \( \sim 1 \) higher than the initial survey, so errorbars should be larger by a factor of \( \sim 1.5 - 2 \).
Significance Histograms

Circumstellar Excess Significance Histogram

Occurrences

Significance

Circumstellar Excess Significance Histogram

Occurrences

Significance
Examples from Recent Analysis (Preliminary)

- **HD219134**
  - Star Model $\chi^2 = 1.045$
  - Star+Dust Model $\chi^2 = 1.192$
  - $F_{\text{dust}}/F_* = (0.217 \pm 0.555)\%$

- **HD9826**
  - Star Model $\chi^2 = 6.840$
  - Star+Dust Model $\chi^2 = 0.733$
  - $F_{\text{dust}}/F_* = (3.032 \pm 0.490)\%$

• Age: $\sim 12$ Gyr
• No detected NIR excess
• No detected FIR excess

• ups And
• Age: $6$ Gyr
• $\sim 5\sigma$ NIR excess
• No detected FIR excess
• Exoplanet host star
• *iot Pcs*
• Age: 3.9 Gyr
• $\sim 5\sigma$ NIR excess
• Detected FIR excess

• 110 Her (Absil excess)
• Age: 2.3 Gyr
• Binary likely
• Detected FIR excess
Summary of Results (Preliminary)

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>F</th>
<th>G-K</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer reservoir</td>
<td>2/9</td>
<td>4/8</td>
<td>1/4</td>
<td>7/21</td>
</tr>
<tr>
<td>No outer reservoir</td>
<td>6/14</td>
<td>2/16</td>
<td>1/21</td>
<td>9/51</td>
</tr>
<tr>
<td>Total</td>
<td>8/23</td>
<td>6/24</td>
<td>2/25</td>
<td>16/72</td>
</tr>
</tbody>
</table>

NO statistically significant correlations yet, but...

- A (35%), F (25%), G-K (8%). $\sim 2\sigma$ result.
- Outer reservoir (33%), No outer reservoir (18%). $>1\sigma$ diff
Conclusions and outlook

- Faint debris disks require very precise fringe visibility measurements (\( \sim 1\% \))
- We have developed a data reduction pipeline which minimizes biases and errors (Nuñez et al. 2016, near submission)
- We have detected 7 new circumstellar excesses among the 37 stars analyzed (Nuñez et al. 2016, in preparation)
- Attributable to hot- and close-in dust in 5 cases. Binarity ruled out in most cases by RV studies
- Mechanism for dust replenishment/trapping is still subject of debate
- To do:
  - Lithium Niobate plates to maximize raw visibilities
  - Observations with S1-S2 equipped with adaptive optics