Results of LBTI’s HOSTS survey and prospects

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Thanks to P. Hinz and S. Ertel

Steward internal symposium – Tucson (September 21, 2018)
The long term goal
The long term goal
The long term goal
The long term goal
The observing challenge

1. Contrast:
   - Visible: $10^{-10}$ fainter
   - IR: $10^{-7}$ fainter

Kaltenneger et al. 2009
The observing challenge

1. Contrast:
   - Visible: $10^{-10}$ fainter
   - IR: $10^{-7}$ fainter
The observing challenge

Visible: $\sim 10^9$
Fomalhaut b but 150x sep

Infrared: $\sim 10^6$
51 Eri but 13x sep
Exoplanet status

Mass – Period Distribution

3779 confirmed exoplanets (+4496 candidates)
The observing challenge
The observing challenge
The observing challenge

Hidden in the Exo Zodi Fog
Talk overview

1. What is an exozodi? Why do we care?

2. What do we know?

3. The HOSTS survey

4. Beyond the HOSTS survey
Talk overview

1. What is an exozodi? Why do we care?

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Zodiacal dust

- Dust inside a few AU
- Power law surface density \( (\alpha \sim -0.5, \text{Kimura \& Mann 1998, Hahn et al. 2002}) \)
- \( T: \text{few } 100K \text{ to } 2000K \) (Kimura \& Mann 1998, Hahn et al. 2002)
- Comet evaporation (Nesvorny et al. 2010)
- Asteroid collision \& P-R drag (Dermott et al. 2002)
- Complex local structure (planetary interaction, local dust creation)

COBE/DIRBE (Kelsall et al. 1998)
Zodiacal dust
The term exozodiacal dust (short exozodi) is used here to refer to warm or hot dust (with $T > 300K$) orbiting around a main sequence star. The zodiacal dust in our Solar System is part of this category. However, exozodis can be much brighter and located at different radial locations than the zodiacal dust. Exozodis are to be distinguished from their colder counterparts, called debris discs, for which the observed dust is produced by quasi steady state collisions in belts (similar to the Kuiper belt) composed of planetesimals and large rocky bodies orbiting at tens of au [77, 160].

- **Warm dust:** Near the habitable zone (HZ, $T \sim 300K$), observed in the mid-IR

- **Hot dust:** Very close to the star, near sublimation distance, observed in the near-IR

- **Common physics:** *No equilibrium collisional cascade* from large bodies over age of the star
Why do we care?

- Most luminous component of planetary systems (after star)
- Gives insight into architecture and dynamics in the innermost regions (near habitable zone)

1. Source of noise

1 zodi = ~300x Earth at 550 nm and 10 µm.
Why do we care?

- Source of noise and confusion for future direct imaging missions
Why do we care?

- Source of noise and confusion for future direct imaging missions

\[ \phi = -0.17 \]

Reduce exozodi by 10x, increase yield by \( \sim 2x \)

Tolerable dust density is \( \sim 15 \) zodis for IR imagers

Stark et al., 2014, 2015

Defrère et al. 2010
Why do we care?

Defrère et al. 2012

2. Source of confusion
Why do we care?

Defrère et al. 2012
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The need for infrared interferometry

- High contrast ($\geq 1:100$), zodi levels $< 1000 \times$ Solar system not detectable with photometry or spectroscopy
- Small angular separation:
  - Inner disc: a few 10 mas
  - Requires high-precision IR interferometry
What do we know?

• Single-dish photometry
  - Spitzer: ~1% of 152 main-sequence stars (Lawler et al., 2009)
  - WISE: ~0.09% of 22000 main-sequence stars (Kennedy et al. 2012)
  - Sensitivity threshold ~1000 zodis

• Infrared interferometry
  - Keck nuller: ~10 detections out of 41 main-sequence stars
    (sensitivity threshold ~250 zodis, Mennesson et al. 2014).
  - Median level of exozodiacal dust < 60 zodis high confidence (95%,
    assuming a log-normal luminosity distribution).
What do we know?

Roberge et al. 2012
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Enters the LBTI

Large Binocular Telescope (LBT) on Mt Graham, Arizona
And the HOSTS team

The Large Binocular Telescope

**Resolution**
Beam combination provides the equivalent resolution of a 22.7-m telescope.

**High Contrast**
The AO system creates an image with a Strehl of >90% at 3.8 µm.

**Sensitivity**
LBT has two 8.4-m mirrors mounted on a single structure (collecting area of a single 11.8-m aperture).
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Key specificities

1. Common mount interferometer
   ⇒ No geometric delay
   ⇒ No long delay line
The LBT interferometer (LBTI)

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The LBT interferometer (LBTI)
Nulling interferometry
Nulling interferometry
Example of observation
Example of observation (2013)

First Stabilized Fringes with LBTI

Open Phase Loop

Closed Phase Loop

Dec. 30, 2013
First-light results: $\eta$ Crv (2014)
First-light results: $\eta$ Crv (2014)
First-light results: η Crv (2014)
First-light results: $\eta$ Crv (2014)

**Disk/star flux ratio ~20%**

4.5% LBTI leak

inner disk location/width

leak prediction

320 au

Defrère et al. 2015
First-light results: η Crv (2014)
First observations with closed phase loop
HOSTS survey results

- Hunt for Observable Signatures of Terrestrial planetary Systems
- NASA funded, managed by JPL: build the LBTI, execute survey
- Carried out at 11 microns (N band)
- Most sensitive exozodi survey!
- 38 stars observed, 11 detections
HOSTS survey results

- Measurements & errors well behaved
- 8 new detections (+3 KIN excesses confirmed at high SNR)

Ertel et al. (2018)
HOSTS survey results

Excess distribution
Sigma of the distribution: 1.12

Uncertainty distribution
Median uncertainty: 0.11%
30% improvement!

Sigma of the distribution: 1.20

Median uncertainty: 0.08%
• Probability that stars **with and without cold dust** have the **same occurrence rate**: $p = 0.003$

• Similar incidence rate for **Sun-like and early type stars** comes at **~4x lower sensitivity** around Sun-like stars
• Probability that stars with and without cold dust have the same occurrence rate: \( p = 0.003 \)

• Similar incidence rate for Sun-like and early type stars comes at \( \sim 4x \) lower sensitivity around Sun-like stars
HOSTS survey results

Poynting-Robertson drag from outside

- Offers sufficient explanation (Kennedy & Piette, 2015)

- Confirmed in detailed modeling (β Leo, Hinz et al., in prep.)

- Some (extreme) systems need other explanation (e.g., η Crv, Defrère et al. 2015)

- Also works for faint outer belts?

Still, better understanding is critical:

- Where is the source (Kuiper belts vs. Asteroid belts)?

- Contribution from other mechanisms, like comet evaporation?
HOSTS survey results

LBTI

Ertel et al. in prep

Wyatt et al. 2005 PR-drag models

\[ F_{dust}/F_\star (11.1 \, \mu m) \]

\[ T_{cold dust} (K) \]
Upper limits on median zodi level on stars without cold dust (95% confidence, assuming lognormal distribution):

- 12 zodis for all clean stars!
Median zodi level

Upper limits on median zodi level
(95% confidence, assuming lognormal distribution):

• 12 zodis for all stars
• 16 zodis for Sun-like stars

For stars without known cold dust

Exo-Earth imaging generally possible!
Main conclusions from HOSTS

- HOSTS survey completed (38 total stars observed, Ertel et al. in prep)
- Many papers to write on existing HOSTS data!
- Exozodi delivered from outer Kuiper/Asteroid belt by PR drag
- Upper limit on median exozodi level 12 zodi
- Exo-Earth imaging generally possible!
Talk overview

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HOSTS prospects

• More observations required:
  • Characterize detected systems (disk geometry, different P.A. and wavelength)
  • Exozodi still major uncertainty in exoplanet yield predictions
  • Some high priority targets (i.e. nearest stars) not observed during baseline survey
  • To tie the phenomenon of zodiacal dust to physical models and proxy markers

• System performance and robustness will improve in the future:
  • Better AO (fainter and more southern stars accessible)
  • New detector (better sensitivity),
  • New optimized data acquisition approach (better sensitivity)
Target vetting for exo-Earth imaging

Upper limits on median zodi level
(95% confidence, assuming lognormal distribution):

- 11.5 zodis for all stars
- 16 zodis for Sun-like stars
- 7.5 for Sun-like stars without LBTI detection!

Still for stars without known cold dust

Exo-Earth imaging generally possible!
Target vetting for exo-Earth imaging

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Still for stars without known cold dust

Exo-Earth imaging generally possible!
Characterization of detected systems

Disk geometry and exact excess from field rotation
Characterization of detected systems

- Search for & characterize structures in dust distribution due to planets
- Rotate on time scale of planetary orbit
- Characterize architectures of habitable zones (presence of planets, mass, orbits)

(e.g., Ertel et al. 2012, Shannon et al. 2015, Bonsor et al. in prep.)
Characterization of detected systems

- Multi-wavelength data trace spectral shape of the emission (grain size) and radial dust distribution
- Constrain dust properties and origin
- Better predict scattered light brightness
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Hi-5: a potential high-contrast thermal near-infrared imager for the VLTI

D. Defrère, M. Ireland
University of Liège, Australian National University

High-contrast interferometry status

Defrère et al. 2018

VLTI and CHARA

VLTI's IWA @ 3.8μm

ELT's IWA @ 3.8μm

VLT's IWA @ 3.8μm

1σ contrast

1 - 10

10

100

1000

Angular separation [mas]

Hi-5 + kernel nulling

Nulling N-band

Nulling K-band

Coronagraphy

NRM
New project: Hi-5

- **L/M-band** high-contrast interferometry on the VLTI (Defrère et al. 2018)
- Leverage the angular resolution of the VLTI and nulling interferometry
- EU-funded for a design study led by the University of Liege
Science case 1: exozodiacal disks

- Thermal near-IR = missing link in current exozodiacal disk models (interactions between hot dust and asteroid belts)
- Measuring the faint end of the exozodi luminosity function (complementary with LBTI in northern hemisphere)

Kral et al. 2018
Science case 2: exoplanets

- L/M-band = sweet spot for direct exoplanet imaging
  - Favorable star/planet contrast
  - Access to planet radius and temperature
  - Molecular bands / nonequilibrium chemistry

Skemer et al. 2014

![Graph showing contrast with respect to a Sun-like star across different wavelengths for various temperatures.](Image)
Science case 2: exoplanets

Angular separation [mas]

1-σ contrast

VLTI and CHARA

Hi-5 + kernel nulling

Nulling N-band

Nulling K-band

VLTI's IWA @ 3.8μm

ELT's IWA @ 3.8μm

VLT's IWA @ 3.8μm

Coronagraphy

NRM

Science case 3: planet formation

- Imaging young stars in nearby star forming regions
  - Search for young, forming planets (e.g., explore the cavities of transitions disks)
  - Need good imaging capabilities in addition to high contrast
  - Prepare for PFI science
Revival of space interferometry in Europe
Temperate Rocky planets are ubiquitous.
OSIRIS-Rex optical spectrum
- Evidence of gas-phase H₂O over the entire planet.
- Substantial concentration of O₂.

OSIRIS-Rex infrared spectrum
- Evidence of CO₂, O₃, CH₄, and H₂O.
- Atmosphere transparent between 8.3 and 12.5 μm (probe of surface temperatures).

Lauretta et al. 2018
Credit: NASA/Goddard/University of Arizona/Arizona State
Direct detection: context

**Flux at 10 microns [mJy]**

**Angular separation [mas]**

- **Space nuller with 100-m baseline**
- **LBTI nuller**
- **ELT/METIS**
- **VLT/VISIR**
- **JWST/MIRI**

*assuming an IWA of $2\lambda/D*
At the moment the LIFE core team consists of

- Sascha P. Quanz (ETH Zurich, Switzerland; Project Coordinator and Science Lead)
- Denis Defrere (University of Liege, Belgium; Technical Lead)
- Olivier Absil (University of Liege, Belgium)
- Adrian Glauser (ETH Zurich, Switzerland)
- Kate Isaak (ESA/ESTEC, The Netherlands)
- Jens Kammerer (Australian National University Canberra, Australia)
- Lucas Labadie (University of Cologne, Germany)
- Sylvestre Lacour (Paris Observatory, France)
- Yamila Miguel (Leiden Observatory, The Netherlands)
- Heike Rauer (DLR, Germany)
- Sarah Rugheimer (University of St. Andrews, Scotland UK)
Comparison with LUVOIR

• Revised exoplanet yield of space nuller (4x 2-m, with 5 mas IWA) based on Kepler stats (Kammerer and Quanz 2018a, Quanz et al. 2018)

• Similar results as LUVOIR (12m) for 200 and 450 K and radii between 0.5 and 1.75 $R_{\text{Earth}}$: 63 (LUVOIR) vs 85 (LIFE) detections.

• For mid-IR nuller, 50% of observed planets are around M stars
Take away messages

- HOSTS is **successful**!
- Many detections to study, much to learn
- Exo-Earth imaging possible! ... but:
  - Still a major uncertainty in exoplanet yield computation
  - Many prime targets not yet observed
- A new VLTI project (**Hi-5**)
  - No high-precision/nulling interferometer in the South
  - Near-IR/mid-IR gap in high-contrast interferometric observations
  - Strong exoplanet science case (~40 better IWA than ELT)
- Revival of space interferometry in Europe (**LIFE** project)
Thank you very much!
Context

see Stone et al. submitted

Terrestrial Planets

probed by Dynamical Models

Giant Planets

probed by LBTI/LEECH survey

Asteroid Belt
~150 K warm dust

exo-zodi probed by
LBTI/HOST survey

Kuiper Belt
~50 K cold dust

debris probed by Herschel, HST and ALMA

debris probed by Spitzer

Courtesy Kate Su
### LIFE: exoplanet yield

- Exoplanet yield based on Kepler stats:
  - 207 \((R < 6R_E)\) planets observable \((V\ \text{band})\), 70 \((J\ \text{band})\), and 38 \((H\ \text{band})\)
  - No significant improvement with contrasts better than \(10^{-10}\)
  - Improving IWA more important at this point

#### Table 5. Instrumental parameters for our baseline scenario for HabEx/LUVOIR.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D)</td>
<td>12 m</td>
<td>Aperture size</td>
</tr>
<tr>
<td>IWA</td>
<td>(2 \lambda_{\text{eff}}/D)</td>
<td>Inner working angle</td>
</tr>
<tr>
<td>(C_{\text{ref}})</td>
<td>1e–10</td>
<td>Achievable contrast performance</td>
</tr>
<tr>
<td>(\lambda_{\text{cen, } V})</td>
<td>554 nm</td>
<td>Central wavelength of (V)-band filter</td>
</tr>
<tr>
<td>(\lambda_{\text{cen, } J})</td>
<td>1245 nm</td>
<td>Central wavelength of (J)-band filter</td>
</tr>
<tr>
<td>(\lambda_{\text{cen, } H})</td>
<td>1625 nm</td>
<td>Central wavelength of (H)-band filter</td>
</tr>
</tbody>
</table>
| \(F_{\text{lim, } V}\) | 3.31e–10 Jy | Sensitivity limit \((V\text{-band)}\)^
| \(F_{\text{lim, } J}\) | 9.12e–10 Jy | Sensitivity limit \((J\text{-band)}\)^
| \(F_{\text{lim, } H}\) | 8.32e–10 Jy | Sensitivity limit \((H\text{-band)}\)^

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Kammerer and Quanz 2018

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![Diagram showing expected number of detectable planets vs. achievable contrast performance for different telescope sizes.](chart.png)
And then? How to identify life?

- Several important molecules to look for (ex: O₂, O₃, CH₄) but no clear/unambiguous biosignatures (false positives!)

- Necessary to better planet atmospheric processes and their evolutionary histories

- **Large sample is required**

- Population analysis:

  Colour-colour or CH₄/O₂/H₂O diagrams will allow to identify families of planets and maybe some anomaly

Wagner et al. 2016
And then? How to identify life?

Domagal-Goldman et al. 2014
Take away messages

Want to know more?

Weinberger et al. (2015): Sample selection
Kennedy et al. (2015): Modeling
Defrère et al. (2015): η Crv
Ertel et al. (2018): First survey results
Ertel et al. (in prep.): Full survey results
Hinz et al. (in prep): β Leo
More to come!