Infrared Imaging of Exoplanets

William C. Danchi

January 5, 2012

ExoPAG #7
In 2009 we had the Exoplanet Community Report:

The exoplanet community’s top priority is that a line of probe-class missions for exoplanets be established, leading to a flagship mission at the earliest opportunity.
4 Infrared Imaging

William Danchi, NASA Goddard Space Flight Center, Chair

Peter Lawson, Jet Propulsion Laboratory, Co-Chair

Detecting Earth-area Planets is Difficult and the Thermal Infrared is a Good Spectral Region

- Detecting light from planets beyond solar system is hard:
  - Earth sized planet emits few photons/sec/m² at 10 μm
  - Parent star emits $10^6$ more
  - Planet within 1 AU of star
  - Exozodi dust emission in target solar system x 300 brighter than earth-area planet for equivalent of ONE Solar System Zodi
Earth Spectrum Peaks in the mid-IR

Earth’s spectrum shows absorption features from many species, including ozone, nitrous oxide, water vapor, carbon dioxide, and methane.

Biosignatures are molecules out of equilibrium such as oxygen, ozone, and methane or nitrous oxide.

Spectroscopy with R ~ 50 is adequate to resolve these features.
Terrestrial Planet Finder Interferometer

**Salient Features**
- Formation flying mid-IR nulling Interferometer
- Starlight suppression to $10^{-5}$
- Heavy launch vehicle
- L2 baseline orbit
- 5 year mission life (10 year goal)
- Potential collaboration with European Space Agency

**Science Goals**
- Detect as many as possible Earth-like planets in the habitable zone of nearby stars via their thermal emission
- Characterize physical properties of detected Earth-like planets (size, orbital parameters, presence of atmosphere) and make low resolution spectral observations looking for evidence of a *habitable* planet and bio-markers such as $O_2$, $CO_2$, $CH_4$ and $H_2O$
- Detect and characterize the components of nearby planetary systems including disks, terrestrial planets, giant planets and multiple planet systems
- Perform general astrophysics investigations as capability and time permit

W. C. Danchi, P.R.Lawson
Laboratory Testbed Milestones

- **MILESTONE #1** – Compensation of intensity and phase demonstrated by Adaptive Nuller testbed. Intensity compensated to 0.2% and phase to 5 nm rms across a 3 μm band centered at 10 μm.
- **MILESTONE #2** – Demonstration of precision formation flying maneuvers in a ground-based robotic testbed, with traceability to flight.
- **MILESTONE #3** – Demonstration of broadband nulling at the flight requirements of $1.0 \times 10^{-5}$, using 34% bandwidth centered at 10 μm. Monochromatic nulls demonstrated to $5 \times 10^{-7}$.
- **MILESTONE #4** – Laboratory demonstration of detection of planet signal $10^6$ times fainter than a star while using array rotation, chopping, and averaging.

View of a chalcogenide glass fiber, in use within the Adaptive Nuller testbed. The fiber can be seen being fed by an off-axis parabola, to the right, prior to the spectrometer and single-pixel detector.

Side view of the periscope assembly of the Achromatic Nulling Testbed.
Sensitivity and Resolution in the Mid-IR

Ground-based interferometry in the IR:
- Limited sensitivity
- Long baselines available
- Good for studying protoplanetary disks

Space-based interferometry:
1. Structurally Connected interferometer (limited baseline length)
   - Exozodi levels for ALL TPF/Darwin stars
   - Debris Disks
   - Characterize Warm & Hot Planets & SuperEarths
2. Formation-flying or tethers (long baselines)
   - Detect and characterize many Earth-sized planets
   - Transformational astrophysics
Observations and some findings

• Advanced imaging with both high-angular resolution and high sensitivity in the mid-infrared is essential for future progress across all major fields of astronomy.

• Exoplanet studies particularly benefit from these capabilities.

• Thermal emission from the atmospheric and telescope(s) limits the sensitivity of ground-based observations, driving most science programs towards space platforms.

• Even very modest sized cooled apertures can have orders of magnitude more sensitivity in the thermal infrared than the largest ground-based telescopes currently in operation or planned.

• We find a mid-IR interferometer with a nulling capability on the ground and a connected-element space interferometer both enable transformative science while laying the engineering groundwork for a future “Terrestrial Planet Finder” space observatory requiring formation-flying elements.
Our main recommendations:

Although we support most of the long-term goals that the Exoplanet Task Force (ExoPTF) recommended for a flagship infrared mission, we recommend a different path forward for the near-term. Specifically, we are not convinced, as the ExoPTF report suggests, that the problem of exozodi levels and debris disks can be solved with ground-based observations to the extent necessary for the formulation of a flagship mission. We are not convinced, in part due to our own experience with the Keck Interferometer, for which the lower limit on exozodi is 100–200 times that of the Solar System zodi level. We expect that the nulling instrument on Large Binocular Telescope Interferometer (LBTI) will reduce this limit substantially for a relatively small sample of stars. We discuss how a probe-class mission in the infrared can measure the exozodi levels down to the level of one Solar System zodi for essentially all of the potential target stars for the eventual flagship TPF/Darwin missions. This step is crucial, not only for the flagship characterization missions, but is also of great value to an astrometric mission because that mission can then focus its searches for Earth-twins around stars with low exozodi levels. Moreover, an infrared probe-class mission has a higher degree of technology leveraging from JWST, and could be undertaken in a relatively short time without undue cost and technology risk. Our summary of recommendations from this chapter follows:

Recommendation: A vigorous technology program, including component development, integrated testbeds, and end-to-end modeling, should be carried out in the areas of formation flying and mid-infrared nulling, with the goal of enabling a probe-scale nulling interferometry mission in the next 2 to 5 years and a flagship mission within the next 10 to 15 years.

Recommendation: The fruitful collaboration with European groups on mission concepts and relevant technology should be continued.

Recommendation: R&A should be supported for the development of preliminary science and mission designs. Ongoing efforts to characterize the typical level of exozodiacal light around Sun-like stars with ground-based nulling interferometry should be continued.
Astro2010
Research & Analysis Recommendations

• **Ground-based interferometry**
  
  – Ground-based interferometry serves critical roles in exoplanet studies. It provides a venue for development and demonstration of precision techniques including high contrast imaging and nulling, it trains the next generation of instrumentalists, and develops a community of scientists expert in their use.
  
  – We endorse the recommendations of the “Future Directions for Interferometry” Workshop and the ReSTAR committee report to continuing vigorous refinement and exploitation of existing interferometric facilities (Keck, NPOI, CHARA and MRO), widening of their accessibility for exoplanet programs, and continued development of interferometry technology and planning for a future advanced facility
  
  – The nature of Antarctic plateau sites, intermediate between ground and space in potential, offers significant opportunities for exoplanet and exozodi studies by interferometry and coronagraphy.

• **Space-based Interferometry**
  
  – Space-based interferometry serves critical roles in exoplanet studies. It provides access to a spectral range that can not be achieved from the ground and can characterize the detected planets in terms of atmospheric composition and effective temperature. Sensitive technology has already been proven for missions like JWST, SIM, and Spitzer, and within NASA’s preliminary studies of TPF
New Worlds Technology Development Program

To achieve New Worlds objective – studying nearby, habitable exoplanets - need **preliminary observations** before choosing a flagship mission:

- Planetary demography over wide range of conditions:
  - Kepler, WFIRST, integrated ground-based program

- Measurement of zodiacal light:
  - Ground-based telescopes.
  - Sub-orbital and explorer mission opportunities.

In parallel, need **technology development** for **competing approaches** to make informed choice in second half of decade

**RECOMMEND $100-200M over decade**

Planned integrated ground-space exoplanet program
A Small Structurally Connected Interferometer; The Fourier-Kelvin Stellar Interferometer (FKSI) Mission

**Key Science Goals:**

- **Observe Circumstellar Material**
  - Exozodi measurements of nearby stars and search for companions
  - Debris disks, looking for clumpiness due to planets
- **Detect >20 Extra-solar Giant Planets**
  - Characterize atmospheres with R=20 spectroscopy
  - Observe secular changes in spectrum
  - Observe orbit of the planet
  - Estimate density of planet, determine if rocky or gaseous
  - Determine main constituents of atmospheres
- **Star formation**
  - Evolution of circumstellar disks, morphology, gaps, rings, etc.
- **Extragalactic astronomy**
  - AGN nuclei

**Technologies:**

- Infrared space interferometry
- Large cryogenic infrared optics
- Passive cooling of large optics
- Mid-infrared detectors
- Precision cryo-mechanisms and metrology
- Precision pointing and control
- Active and passive vibration isolation and mitigation

**Key Features of Design:**

- ~0.5 m diameter aperture telescopes
- Passively cooled (<70K)
- 12.5 m baseline
- 3 – 8 um (or 10 TBR) micron science band
- 0.6-2 micron band for precision fringe and angle tracking
- Null depth better than $10^{-4}$ (floor), $10^{-5}$ (goal)
- R=20 spectroscopy on nulled and bright outputs of science beam combiner

PI: Dr. William C. Danchi
Exoplanets & Stellar Astrophysics, Code 667
NASA Goddard Space Flight Center
Debris Disk Sensitivity

Expected performance for Pegase and FKSI compared to the ground-based instruments (for 30 min integration time and 1% uncertainty on the stellar angular diameters).

Sky coverage after 1 year of observation of GENIE (dark frame), ALADDIN (light frame) and Pegase (shaded area) shown with the Darwin/TPF all sky target catalogue. The blue-shaded area shows the sky coverage of a space-based instrument with an ecliptic latitude in the [-30°, 30°] range (such as Pegase). The sky coverage of FKSI is similar to that of Pegase with an extension of 40° instead of 60°.

Results of simulations using the TPF performance simulator of Dubovitsky & Lay for an enhanced FKSI but with 1-, 1.5-, and 2-m diameter telescopes. $N_x$ is the number of 1 or 2 $R_{\text{Earth}}$ exoplanets detected in the population of F, G and K dwarf stars within 30 pc. $N_{\text{spec}}$ are the number of these target planets for spectroscopic characterization of the atmosphere.
Simulations of FKSI performance with 1-2 m class telescopes at 40K and a 20-m baseline demonstrate that many 2 R_{Earth} super-Earths and a few Earth-twins can be discovered and characterized within 30 pc of the Sun.

Discovery space for exoplanets for FKSI and other mission concepts and techniques.
FKSI

• Most recent work in 2009-2010 time frame – mission design studies:
  – Center wavelength from 5 to 10 μm
  – Baseline from 12.5 m to 20 m
  – Mirror diameter from 0.5 m to 1.0 m
  – Passive cooling to 40 K
  – JWST cryocooler for detectors operating at longer wavelengths
  – Did performance calculations to see how many super-Earths and Earth-sized planets could be detected
  – Work was published in SPIE in 2010, and other conference proceedings

• Currently working with PERSEE for FKSI related issues:
  – Test imaging capabilities with realistic scene consisting of star, planet, and exozodi
  – Test of pathlength control for realistic boom and reaction wheel noise sources
Executive Summary
Workshop on the future of the bank PERSEE
Tuesday, December 11, 2012
Version 0.1
We participated in the workshop:
• Vincent Coudé du Foresto, Raphael Galicher, Sophie Jacquinod, Emilie Lhome, Jean-Reess Michel, Daniel Rouan, Gérard Rousset, Didier Tiphène (Obs. Paris - LESIA)
• Jacques Berthon Olivier La Marle (CNES)
• Bruno Lopez, Jean-Luc Menut, Aurélie Marcotto, Florentin Millour (OCA)
• Jean-Baptiste Daban, Gaetan Dalla Vedova, Romain Petrov (U. Nice)
• Frédéric Cassaing Beatrice Sorrento (ONERA)
• Alain Léger, Marc Ollivier (IAS)
• Samuel Heidmann, Francois Henault, Pierre Kern, Guillermo Martin (IPAG)
• Peter Schuller (U. Cologne)
• Amandine Caillat (OAMP)
• Michel Tallon (Obs. Lyon)
• Bill Danchi (NASA Goddard)
• Julien Lozi (for Skype)
• Olivier Absil (U. Liege)
• Adrian Belu
The papers presented at this meeting are available online at:
http://www.lesia.obspm.fr/persee/forum-11-dicembre/article/programme
General context

Science cases: exoplanet spectroscopy + exozodiacal dust imagery
2006: Pegase proposal to ESA Cosmic-Vision (postponed)

\[ \lambda / 2B = 0.5 - 10 \text{ mas} \]

\[ \lambda = [2.5-5] \mu\text{m}, R_\lambda = 60 \]

Hot Jupiters \(\Rightarrow\) contrast = \(10^4\)

\[ B = 50 - 500 \text{ m} \]

\[ D = 40 \text{ cm} \]

Is deep null enough stable with formation-flying spacecrafts? \(\Rightarrow\) Need ground validation
From CNES meeting

Worldwide performances

Requirements for exoplanets observation

PERSEE goal
$10^{-4} \pm 10^{-5}$

PERSEE Polychr. light
$8.8 \times 10^{-6} \pm 1.5 \times 10^{-6}$

PERSEE Monochr. light
$5.6 \times 10^{-6} \pm 2 \times 10^{-7}$

Atelier PERSEE - CNES Paris - 11 décembre 2012
Conclusions and perspectives

Already done
- PERSEE achieves very efficient polychromatic null in non-polarized light
- LQG control loop maintains OPD at less than mm rms in presence of representative disturbances induced by reaction wheels (high frequency) with a significant amplitude

Still to be done
- Fringes acquisition with a initial drift speed (150µm/s) ➔ in progress
- Simulated complex targets (star + faint planet + exozodi) ➔ PhD starting
- Simulation of FKSI disturbances ➔ coming soon?
# Technology Investments

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIM Technology up to Phase B</td>
<td>$600 M</td>
</tr>
<tr>
<td>Keck Interferometer</td>
<td>$120 M</td>
</tr>
<tr>
<td>LBTI</td>
<td>$20 M +</td>
</tr>
<tr>
<td>JPL Testbeds (AcNT, AdNT, PDT, etc.)</td>
<td>$60 M</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$800 M +</strong></td>
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</tbody>
</table>

A number of smaller mission concepts and testbeds, such as FKSI, PICTURE, SPIRIT and WIIT testbed, BETTII, and Nulling Coronagraph Testbed(s), also have contributed, at the cost of $10 M+

**ARE WE GOOD STEWARDS OF THE TAXPAYER’S MONEY WHEN WE HAVE NO MISSION IN THE QUEUE BASED ON THESE INVESTMENTS?**
Where do we go from here?

- Need to examine the state of the art for IR interferometry in space and assess the feasibility of a low-cost explorer, midex, or probe mission.
- The Technical Readiness Levels for most all of the needed technologies are at 6 or above, with a few exceptions, given the completion of the testbeds and JWST technologies.
- Design studies are needed to clarify cost and the few remaining technologies needed.
- Interest from Europe for international collaborations is still strong.
- Need to find new creative ways to work together within NASA itself and to foster international collaboration.
- It would be beneficial to open LBTI to broader NASA science given the cutoff of funding to the Keck Interferometer.
- Need continued support from US exoplanet community and HQ for further work in this area.
- Consequence of no action or a lack of a commitment to move forward on a concrete mission will be a withering of the field in the time frame of ~5 years (especially after LBTI exozodi activity ends.)
Backup
TPF-I Technology Goals and Accomplishments

• Architecture
  – Adoption of Emma X-array by TPF-I and Darwin as basis for mission design
  – Demonstration of agreement between independent performance models of Emma X-Array and comprehensive target star catalog
Technical Readiness for a Small Structurally Connected Interferometer

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>TRL</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Cryocoolers</td>
<td>6</td>
<td>Source: JWST</td>
</tr>
<tr>
<td>2</td>
<td>Precision cryogenic structure (booms)</td>
<td>6</td>
<td>Source: JWST</td>
</tr>
<tr>
<td>3</td>
<td>Detectors (near-infrared)</td>
<td>6</td>
<td>Source: HST, JWST NIRCAM</td>
</tr>
<tr>
<td>4</td>
<td>Detectors (mid-infrared)</td>
<td>6</td>
<td>Source: Spitzer IRAC, JWST MIRI</td>
</tr>
<tr>
<td>5</td>
<td>Cryogenic mirrors</td>
<td>6</td>
<td>Source: JWST</td>
</tr>
<tr>
<td>6</td>
<td>Optical fiber for mid-infrared</td>
<td>4</td>
<td>Source: TPF-I</td>
</tr>
<tr>
<td>7</td>
<td>Sunshade</td>
<td>6</td>
<td>Source: JWST</td>
</tr>
<tr>
<td>8</td>
<td>Nuller Instrument</td>
<td>4-5</td>
<td>Source: Keck Interferometer Nuller, TPF-I project, LBTI</td>
</tr>
<tr>
<td>9</td>
<td>Precision cryogenic delay line</td>
<td>6</td>
<td>Source: ESA Darwin</td>
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*Note: The requirement for the FKSI project is a null depth of $10^{-4}$ in a 10% bandwidth. Laboratory results with the TPF-I testbeds have exceeded this requirement by an order of magnitude (Lawson et al. 2008).*
Cost Estimates

Over the years we have done grassroots, PRICE H, and Resource Analyst Office parametric estimates:

• Cost is $635 M for a 2 year minimum science mission, including $160 M for LV
• Thus it is $475 M without LV, well below guidance of $600-800 M without LV
• This is at 50% probability on the “S” curve
• At 70%, cost estimate is $600 M without LV

• We have around $100-200 M for mission growth while remaining within cost box.
  • Desirable trades include increasing apertures to 1m, telescopes to 40K, and wavelength range from 5-15 um, baseline to 20 m.
## Recent Design Studies: Enhanced FKSI

<table>
<thead>
<tr>
<th>Current design</th>
<th>Enhanced design</th>
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<tbody>
<tr>
<td>Telescope diameter</td>
<td>0.5 m</td>
</tr>
<tr>
<td></td>
<td>from 1 to 2 m</td>
</tr>
<tr>
<td>Baseline</td>
<td>12.5 m</td>
</tr>
<tr>
<td></td>
<td>20 m</td>
</tr>
<tr>
<td>Wavelength range</td>
<td>from 3 to 8 µm</td>
</tr>
<tr>
<td></td>
<td>from 5 to 15 µm</td>
</tr>
<tr>
<td>Telescope temperature</td>
<td>down to 60 K</td>
</tr>
<tr>
<td></td>
<td>down to 40 K</td>
</tr>
<tr>
<td>Field of regard / Sun shade</td>
<td>+/- 20 °</td>
</tr>
<tr>
<td></td>
<td>&gt; +/- 45 °</td>
</tr>
</tbody>
</table>

Recent Design Studies: Enhanced FKSI
Upgraded FKSI Detects many more Super-Earths, $R > 2 R_{\text{Earth}}$

- $F0V$ $R < 1.35$ AU
- $G0V$ $R < 0.95$ AU
- $K0V$ $R < 0.55$ AU
- $M0V$ $R < 0.1$ AU

Defrere et al. 2009
### Basic Assumptions:

- SNR = 5 for detection
- SNR = 10 for spectroscopy (R = 20 at 10 µm)
- 3 visits
- < 2 years total
- < 7 days total per star
- \( T_{\text{Earth}} = 288 \) K
- Earth albedo = 0.3
- Inclination angle of planet orbit = 45°
- Sunshade FOR = +/- 45°
- 1 Solar System Zodi Exozodi

### Recent Performance Study Results

**Ref:** Dubovitsky & Lay 2004

Danchi, Lopez et al. 2009

| Enhanced design | Tel = 1 m | | | | |
|-----------------|-----------|---------|---------|---------|
| \( R_{\text{Planet}} \) | Total | \( N_F \) | \( N_G \) | \( N_K \) | \( N_{\text{Spec}} \) |
| 1 \( R_{\text{Earth}} \) | 4 | 0 | 1 | 3 | 4 |
| 2 \( R_{\text{Earth}} \) | 34 | 6 | 16 | 12 | 16 |

| Tel = 1.5 m | | | | | |
|-----------------|-----------|---------|---------|---------|
| \( R_{\text{Planet}} \) | Total | \( N_F \) | \( N_G \) | \( N_K \) | \( N_{\text{Spec}} \) |
| 1 \( R_{\text{Earth}} \) | 15 | 0 | 7 | 8 | 4 |
| 2 \( R_{\text{Earth}} \) | 95 | 35 | 48 | 12 | 27 |

| Tel = 2.0 m | | | | | |
|-----------------|-----------|---------|---------|---------|
| \( R_{\text{Planet}} \) | Total | \( N_F \) | \( N_G \) | \( N_K \) | \( N_{\text{Spec}} \) |
| 1 \( R_{\text{Earth}} \) | 29 | 3 | 14 | 12 | 12 |
| 2 \( R_{\text{Earth}} \) | 138 | 65 | 61 | 12 | 43 |
Enhanced Discovery Space For Super Earths with upgraded FKSI
FKSI Characterization/Discovery Space for Exoplanets
Preliminary Mechanical Design for Enhanced FKSI
More Recommendations on R&A Support

• **Theory support:**
  – *We will require sustained support of strong astrobiology and atmospheric chemistry programs.*

• **Agency Coordination & Programmatic Strategy**
  – *NASA and NSF goals, makes it an ideal topic for coordination between the agencies, and we urge NASA and NSF staff to leverage this relationship to cover the full breadth of exoplanet science and technology*.

• **International Coordination, Collaboration, & Partnership**
  – *The relationships forged between US and European collaborators should be fostered during the next decade for further studies of small mission and flagship mission concepts. A new letter of agreement is necessary to further future collaborations.*