Terrestrial Planet Finder
Nulling Interferometry

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April 8, 2004
<table>
<thead>
<tr>
<th>Outline</th>
</tr>
</thead>
<tbody>
<tr>
<td>• What is TPF?</td>
</tr>
<tr>
<td>• Infrared signatures</td>
</tr>
<tr>
<td>• What can we learn?</td>
</tr>
<tr>
<td>• Nulling interferometry</td>
</tr>
<tr>
<td>• Current nulling activities</td>
</tr>
<tr>
<td>• Summary</td>
</tr>
</tbody>
</table>
With TPF we want to search for earth-like planets around nearby stars.

Why earth-like planets?
- To what extent is our Solar System and our Earth unique?
- Is life common or not?

What is an earth-like planet?
- A rocky planet of size similar to the earth
- Not too small or the planet will lose its atmosphere
- Not too big or it will be a gas giant
- Not too hot or too cold, so liquid water is present
- If possible, we would like to search for evidence of life

The problem is that it is very hard to detect an earth-like planet!
What don't we know about Extra-Solar Planets

• Key questions:
  – Are the planets *gaseous giants*, like Jupiter or Saturn?
  – Are they *rocky*, like the Earth?
  – What are their *ages*?
  – When did they form in relation to star and disk system?
  – To what extent does exo-zodiacal emission affect our ability to detect Earth-like planets?

• Basic facts we want to learn about a planet:
  – *Temperature*
  – *Radius*
  – *Mass* (known only within $\sin i$ ambiguity for presently known planets)
  – *Density*
  – Type of atmosphere and basic constituents
You can search for planets directly either from reflected starlight or re-radiated starlight.

Notice that different planets have different spectra in the infrared.

DesMarais et al. (2002)
Molecules in the Earth’s atmosphere change the spectrum substantially away from a blackbody curve.

Different molecules have different characteristic atmospheric features, which have widths on the order of $\frac{1}{2}$ micron, and large depths.
Desire to observe simultaneously both:
- Oxidized species such as O₃, CO₂, NO₂, SO₂
- And Reduced species such as CH₄, NH₃, H₂S

Ozone and Methane are probably best IR indicators of life

Ozone is an essential indicator of oxygen content in the atmosphere

Direct detection of water at 6.3 microns is highly desirable

These considerations suggest mid-infrared wavelength coverage from 6 microns to 17 microns is needed for best results
Detecting Earth-like Planets is Difficult

- 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
  - Dust in target solar system $\times 300$ brighter than planet
- Finding a firefly next to a searchlight on a foggy night
How to obtain physical information from infrared data

- If you *detect* the planet at *two different wavelengths* (measure the flux at those wavelengths) you can get the *temperature* (color temperature)
- From the *measured fluxes* and *color temperature* you can determine the *radius* of the planet (photometric size from the infrared flux method)
- If you *track the planet with time*, and measure the orbit, you eliminate the *sin i* ambiguity, and improve the estimate of the *mass* (for presently known planets)
  - From the *mass* and the *radius*, estimate *density*
  - *(May already have some masses from SIM)*
- If you measure at a modest spectral resolution, you can determine what molecules and their abundance, temperature and density are present in the atmosphere
  - Ultimately need radiative transfer models
Why IR Interferometry and Nulling?

- Interferometry is a technique that gives us the highest spatial resolution at a particular wavelength, compared to a classical filled aperture telescope.
- Resolution is important because the planets are close to their stars, typically 1 AU for an earth-like planet around a G2 dwarf star like the Sun.
- At a distance of 10 pc, this gives angular resolution requirement of ~0.1 arcsec, or 0.03 arcsec at 30 pc.
- An IR interferometer with modest baselines matches these requirements very well --
  - Resolution of an interferometer is ~λ/2B.
  - Then if λ ~ 6-17 μm a baseline of 30 m gives a resolution of about 0.04-0.12 arcsec.
- Infrared signal of planet is expected to be less dependent on orbital phase of planet than at visible wavelengths.
- Nulling is a method to reduce the star flux by a large amount and has been proven in the laboratory.
What kind of spectral resolution is needed?

- **Narrowest feature** in 10 μm band is about 0.5 μm wide, *typical* features around 1 μm wide
- Sample with about 2 resolution elements across the features:
  - Implies $\Delta \lambda \sim 0.25$-0.5 μm
  - Resolution R is $\lambda/\Delta \lambda \sim 10/0.25 - 10/0.5 \sim 20$-40
- We picked R~25-30 as a good round number
A simple interferometer

- You get a peak when pathlengths are equal on both sides -- "white light fringe"

- You get a null when pathlengths differ by one half a wavelength -- a "dark fringe"

Fringe Envelope $\propto d^{-1}$

Fringe Spacing $\propto \lambda/D$
A simple nulling interferometer

- You get a null when pathlengths are equal on both sides -- "white light null fringe"

- You get a peak when pathlengths differ by one half wavelength -- a "bright fringe"

Fringe Envelope $\propto d^{-1}$
Fringe Spacing $\propto \lambda/D$
A Simple Example of an Interferometric Detection of a Planet

Interferometric Exo-Planet Detection

In this example we see the response of the interferometer varies as a function of rotation angle of the baseline. The maximum signal is at the far left panel, the minimum signal at the third panel.
TPF Interferometer will need deep and stable interferometric nulling, over a broad MidIR bandwidth, for long observation periods, at cryogenic temperatures to detect planets.

- Specifically:
  - Null Depth: $10^{-6}$
  - Null Stability: $10^{-7}$
  - Optical Bandwidth: 7 – 12 um (50%)
  - Operating Temperature: 77K
  - Observation Period: 1000 – 10,000 sec (~20 min – ~2.5 hours)
  - Off-axis planet flux: $10^{-5}$

- The Achromatic Nulling Testbeds is demonstrating progress toward this ultimate milestone

- Here’s how we’re doing it…
### Ultimate Nulling Capability

<table>
<thead>
<tr>
<th>Objective</th>
<th>TPF Flight</th>
<th>Testbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Null depth</td>
<td>$10^{-5}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Null stability</td>
<td>$10^{-8}$</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Timescales</td>
<td>$10^4$ s</td>
<td>$10^3$-$10^4$ s</td>
</tr>
<tr>
<td>Temperature</td>
<td>40 K</td>
<td>77 K</td>
</tr>
</tbody>
</table>

TPF - Gappinger
A quick review of nulling (I)

\[ I(\Delta x) = \frac{I_0}{2} \left[ 1 + \cos\left(\frac{2\pi}{\lambda} \Delta x\right) \right] \]
A quick review of nulling (II)

Achromatic!

\[ I(\Delta x) = \frac{I_0}{2} \left[ 1 + \cos\left(\frac{2\pi}{\lambda} \Delta x + \pi\right) \right] \]

\[ I(\Delta x) = \frac{I_0}{2} \left[ 1 - \cos\left(\frac{2\pi}{\lambda} \Delta x \right) \right] \]

Nulling Interferometer

Fringe Pattern from Nulling Interferometer
Key Components of a Nulling Interferometer

- Source and single mode filter
- Source Split
  - Planet Light Injection
  - Or Pseudo-achromatic
- Achromatic Field Flip
- Path length control
  - Air Delay
- Recombination
- Output single mode filter and detector
- Ancillary:
  - Chopper
  - Shutters
Warm Achromatic Nulling Testbed

- Demonstrate the physics of deep nulling under moderately easy conditions
  - 300K Work environment
  - Table top experiment
  - Preliminary motion control with off-the-shelf components
- Will be limited in the performance by the detector
  - Primarily a problem for white light observations
    - Difficult to get bright broadband IR source
- Deep laser nulling has been accomplished
- White light observations with bandwidths of 20% - 30% are currently under investigation
Nulling with Phase Plates

- Pseudo-achromatic Field Flip

\[ \varphi(\lambda) = \sum_{i} \frac{2\pi}{\lambda} n_i(\lambda) t_i = \pi \]

- Setup for 9.3 to 12 micron bandwidth gives null depth \(4.8 \times 10^{-5}\)

- Prisms add -76.2 micron ZnSe in one telescope beam

- Delay line adds +188.3 micron air in one telescope beam

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**Phase for Air Delay and Air/Glass Delay**

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**Net phase for ZnSe and Air Solution**

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April 8, 2004  pg 21
Warm Achromatic Nuller: Current Status

- Achieved 1,000,000:1 null with a laser
- Achieved 10,000:1 null for 30% bandwidth infrared source
- Building 3 testbeds to pursue 100,000:1 null for 20% bandwidth IR source
Achromatic Nulling Testbed

- $10^{-6}$ Null depth with 10.6 um laser

- $10^{-4}$ Null depth with 30% BW at 10um
  
  Goal is $10^{-5}$ Null with 25% BW
Summary

- Nulling interferometry will allow parent star to be dimmed sufficiently to detect planet
- Laboratory results are showing progress toward ultimate null depth requirements
- Current experiments are limited by detector noise
  - Need brighter source