Techniques for direct imaging of exoplanets

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1. Where lies the challenge?
2. Contrasts required for ground observations?
3. Push the contrast limit - Recycle!
1. Where lies the challenge?
The telescope aperture?

Take an 8m telescope observing at 1μm wavelength.

<table>
<thead>
<tr>
<th>Distance star [pc]</th>
<th>Can it resolve the planet and its host star?</th>
<th>Can it collect enough photons from the planet?</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>10^10</td>
<td>10^10</td>
</tr>
<tr>
<td>1</td>
<td>10^9</td>
<td>10^9</td>
</tr>
<tr>
<td>10</td>
<td>10^8</td>
<td>10^7</td>
</tr>
<tr>
<td>100</td>
<td>10^7</td>
<td></td>
</tr>
</tbody>
</table>

Telescope aperture is not the primary challenge (except for the coolest exoplanets)
1. Where lies the challenge?

The coronagraph?

Current coronagraphs achieve contrast levels up to $10^{-10}$ for diffraction limited wavefronts.

1. Where lies the challenge?
Adaptive optics & speckle suppression techniques

For the speckles that made their way to the detector:
Spectral Differential Imaging (Racine et al., PASP 1999)

The primary difficulty of high-contrast imaging is:
get a large telescope,


design a coronagraph,


flatten the wavefront and suppress the residual speckles.
Techniques for direct imaging of exoplanets

1. Where lies the challenge?
   • Large telescopes are only required for the coolest exoplanets
   • The primary issue for exoplanet imaging is scatter in the atmosphere and on the imperfect telescope optics

2. Contrasts required for ground observations?
2. What are the contrasts achievable from ground? 

Comparison of 4 exoplanet surveys

- 4m telescope
  - Adaptive Optics
  - Lyot coronagraph
- 6m & 8m telescopes
  - Adaptive optics
  - Spectral Differential Imaging
- 8m telescope
  - Adaptive optics
  - Angular Differential Imaging
- 8m telescope
  - Adaptive optics
  - Lyot coronagraph
  - Spectral Differential Imaging
  - Angular Differential Imaging

The most sensitive survey (NICI): contrasts down to $\sim 10^{-6.5}$

Liu et al, SPIE 2010
2. What are the contrasts achievable from ground?

The ultimate limit

<table>
<thead>
<tr>
<th>Contrast at 0.5” separation</th>
<th>Acceptable wavefront error</th>
<th>Acceptable wavefront error</th>
<th>Required AO correction frequency [Hz]</th>
<th>Required magnitude (H band)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^{-6})</td>
<td>(\lambda /4400)</td>
<td>(\lambda /88)</td>
<td>930</td>
<td>6.9</td>
</tr>
<tr>
<td>(10^{-7})</td>
<td>(\lambda /14000)</td>
<td>(\lambda /280)</td>
<td>2900</td>
<td>3.2</td>
</tr>
<tr>
<td>(10^{-8})</td>
<td>(\lambda /44000)</td>
<td>(\lambda /880)</td>
<td>(10^4)</td>
<td>-0.6</td>
</tr>
<tr>
<td>(10^{-9})</td>
<td>(\lambda /140000)</td>
<td>(\lambda /2800)</td>
<td>(3 \cdot 10^4)</td>
<td>-4.3</td>
</tr>
<tr>
<td>(10^{-10})</td>
<td>(\lambda /440000)</td>
<td>(\lambda /8800)</td>
<td>(10^5)</td>
<td>-8.1</td>
</tr>
</tbody>
</table>

Stapelfeldt, IAU symposium, 2006

The ultimate contrast limit for a solar type star at 10pc \((H=3)\) is \(10^{-7}\)

With added speckle subtraction techniques : \(10^{-8}\)
Techniques for direct imaging of exoplanets

1. Where lies the challenge?
   (correction of residual speckles)
2. Contrasts required for ground observations?
   For a solar twin at 10pc, required contrast $> 10^{-8}$
3. Push the contrast limit - Recycle!
Recycle the photons absorbed by the coronagraph to produce destructive interferences with the speckles.

3. Push the contrast limit - Recycle!

3. Push the contrast limit

We reached contrasts above $10^{-12}$ back in 1919...

Stellar wavefront is blocked ...

... before it is distorted by atmospheric turbulence

... and imperfect telescope optics.

See e.g. Cash et al., SPIE, 2007

External occulters: stellar light never enters the telescope.
Conclusions

1. Where lies the challenge?
   Large telescopes are only required for the coolest exoplanets.
   The primary issue for exoplanet imaging is scatter in the atmosphere and on the imperfect telescope optics.

2. Contrasts required for ground observations?
   For a solar twin at 10pc, the maximum achievable contrast from ground is $10^{-8}$.

3. Push the contrast limit – Recycle!
   The contrast limit can be increased to $\sim 10^{-10}$ by recycling the photons absorbed by the coronagraph, and producing destructive interferences with the speckles.