The Detection of Planets in Discs Through IR Interferometry

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Planet-Disc Connection
Cambridge, 17-20 July 2006
Outline

• Astrophysical requirements and instrumental specifications
  – Contrast
  – Spatial resolution

• Optical long baseline interferometry today
  – Short introduction
  – Available instruments

• Current status of planet detection work
  – AMBER/VLTI
  – IOTA and CHARA

• Planets in discs: first evidence?
  – FU Ori and AB Aur cases

• Detection of planetary gaps in discs
  – Methodology
  – Prospects with PEGASE and DARWIN

• Summary
Astrophysical requirements and instrumental consequences
Astrophysical requirements
How to directly detect a planet?

• 2 main astronomical requirements:
  – Separation between the star and the planet:
    → **High angular resolution**
  – Contrast between the star and the planet:
    → **High dynamic range observations**

• Which instruments available?
  – Adaptive optics
  – Stellar Coronography
  – Long-Baseline Interferometry
Imaging techniques
Exoplanet imaging

- **Advantages**
  - Direct detection of the planet photons:
    \[ F(T_{\text{eff}}, \text{mass}, \text{age}) \]
  - Determination of the orbit, with no ambiguity on \( M \cdot \sin(i) \)
  - Characterization: albedo, temperature, chemical composition
    \[ \Rightarrow \text{test of atmospheric models, of evolution models} \]
  - Access to a new parameter space (mass, separation, age)
    - Distant Planets
    - Planets around young stars
    - Relatively large separations (\( P > \) several years)
  - Access to stars of all spectral types
    - Early-type stars
    - Active stars

- **Cost:** Instrumental capacity is very stringent
**Angular resolution**

Diffraction limit of an optical instrument: $1.22 \frac{\lambda}{D}$

- Visible range @ 0.5 $\mu$m: $12 \ (D/10m)^{-1}$ mas
- Near-infrared range @ 2 $\mu$m: $48 \ (D/10m)^{-1}$ mas
- Thermal mid-infrared @ 10 $\mu$m: $250 \ (D/10m)^{-1}$ mas

<table>
<thead>
<tr>
<th></th>
<th>1.22$\lambda$/D</th>
<th>0.1 AU</th>
<th>1AU</th>
<th>5AU</th>
<th>30AU</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3pc</td>
<td>30mas</td>
<td>0mas</td>
<td>1.5''</td>
<td>9''</td>
<td></td>
</tr>
<tr>
<td>10pc</td>
<td>10mas</td>
<td>0.1''</td>
<td>0.2''</td>
<td>3''</td>
<td></td>
</tr>
<tr>
<td>25pc</td>
<td>40mas</td>
<td>0.2''</td>
<td>1.2''</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100pc</td>
<td>1mas</td>
<td>0.1''</td>
<td>0.3''</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
First results with AO

2M1207 (Chauvin et al. 2004)

GQ Lup (Neuhäuser et al. 2005)
Optical long baseline interferometry
Optical interferometry

Adaptive Optics

Multi telescope interferometry

Detection of Planets in Discs Through IR Interferometry (Cambridge, July 2006)
Principle of interferometry

Visibility amplitude $V(u,v)$

Visibility Phase $\Phi(u,v)$

Point, unresolved object

Normalized intensity

Detection of Planets in Discs Through IR Interferometry (Cambridge, July 2006)
Visibility amplitude changes due to the presence of a faint companion

\[ D = 10 \text{ mas}; \lambda = 2 \mu\text{m} \]

\[ s = 25 \text{ mas}; l_1/l_2 = 0.1; D_1 = 5 \text{ mas}; \lambda = 2 \mu\text{m} \]
Visibility phase changes due to the presence of a faint companion

Interferometer
Resolution ~ 1.5mas

Star continuum
Companion line

\[ \phi(\lambda) \sim 2\pi \theta \]

Le Bouquin (2005)
## Interferometers involved in YSO research

<table>
<thead>
<tr>
<th>Facility</th>
<th>Instrument</th>
<th>Wavelength (microns)</th>
<th># tel.</th>
<th>Tel. Diam. (m)</th>
<th>Baseline (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Existing facilities</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PTI</td>
<td>V²</td>
<td>H, K</td>
<td>3</td>
<td>0.4</td>
<td>80-110</td>
</tr>
<tr>
<td>IOTA</td>
<td>V², CP</td>
<td>H, K</td>
<td>3</td>
<td>0.4</td>
<td>5-38</td>
</tr>
<tr>
<td>ISI</td>
<td>Heterodyne</td>
<td>11</td>
<td>2 (3)</td>
<td>1.65</td>
<td>4-70</td>
</tr>
<tr>
<td>KI</td>
<td>V²</td>
<td>K</td>
<td>2 (4/6)</td>
<td>10 (1.8)</td>
<td>80 (135)</td>
</tr>
<tr>
<td>(nulling)</td>
<td>(nulling)</td>
<td>(10)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VLTI</td>
<td>AMBER: V², CP</td>
<td>1-2.5 / spectral</td>
<td>3 (8)</td>
<td>8.2 (1.8)</td>
<td>40-130 (8-200)</td>
</tr>
<tr>
<td>MIDI: V², V</td>
<td>8-13 / spectral</td>
<td>2 (4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHARA</td>
<td>V², CP, Imaging</td>
<td>1-2.5 (/ spectral)</td>
<td>2-(6)</td>
<td>1</td>
<td>50-350</td>
</tr>
<tr>
<td><strong>Future facilities</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LBT</td>
<td>V², nulling</td>
<td>Imaging, nulling</td>
<td>2</td>
<td>8.4</td>
<td>6-23</td>
</tr>
</tbody>
</table>

**Millan-Gabet (PPV, 2005)**

*Detection of Planets in Discs Through IR Interferometry (Cambridge, July 2006)*
The Very Large Telescope Interferometer

<table>
<thead>
<tr>
<th></th>
<th>AMBER</th>
<th>MIDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral coverage</td>
<td>$J, H, K'$ (1 − 2.4 μm)</td>
<td>$N$ (8 − 12 μm)</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>35, 1000, 10000</td>
<td>100</td>
</tr>
<tr>
<td>Beams combined</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Lim. mag. with UTs (ATs)</td>
<td>$K = 1.3$ (9.8)</td>
<td>$N = 5$ (1.8)</td>
</tr>
<tr>
<td>Field of view</td>
<td>0.06 − 0.24″</td>
<td>0.26 − 1.14″</td>
</tr>
<tr>
<td>Min. fringe spacing ($\lambda/B$)</td>
<td>1-2 mas</td>
<td>10 mas</td>
</tr>
</tbody>
</table>

The AMBER Instrument at the VLT Interferometer

The MIDI Instrument at the VLT Interferometric Laboratory on Paranal

Detection of Planets in Discs Through IR Interferometry (Cambridge, July 2006)
Current status of planet detection work
Detection of Planets in Discs Through IR Interferometry

Principle of differential interferometry

Actual measurements

Petrov et al. (2005, IAU200)
The shape of the phase is due to a combination of imperfect calibration:
- change of the fiber dispersion with temperature
- chromatic differential dispersion in the tunnels.

Note that the effect is extremely small (0.01 rad) with a statistic error 4x larger than the expected value from fundamental noise.
Phase closure in function of $\lambda$

- Phase closure eliminates atmospheric dispersion effects
- It does not eliminate detector effects
- It has a SNR cost:
  - 4.5 more time
  - 6.75 more UT nights

Petrov (2006, VLTI Shool)

Detection of Planets in Discs Through IR Interferometry (Cambridge, July 2006)
Measuring Spectra of Hot Jupiters

Monnier (2006, VLTI Shool)
Precision Closure Phase
State of the Art

Monnier (2006, VLTI Shool)
First Peek at CHARA Closure Phases

Zhao et al. (2006, SPIE)
First Peek at CHARA Closure Phases

Zhao et al. (2006, SPIE)
First Peek at CHARA Closure Phases

Zhao et al. (2006, SPIE)
Detection of hot giant exoplanets through IR interferometry

- Still under investigation:
  - Petrov et al. with AMBER/VLTI: 51 Peg, $\tau$ Boo
    For the moment 4x above the signal (dispersed)
  - Monnier et al. with MIRC/CHARA:
    For the moment 3-4x above the signal (broad band)
  - Swain et al.: observation of HD 209458b planned with AMBER

- Should been within reach soon but a limited number of targets: 51 Peg, $\tau$ Boo, ...

- Maybe attempt younger host stars?
Planets in protoplanetary discs?
Detection of Planets in Discs Through IR Interferometry

FU Orionis: a wealth of NIR interferometric data

- 42 nights of observation
- 3 interferometers
- 6 baselines
- 287 visibilities

Fig. 1. \((u, v)\) tracks corresponding to the observations of FU Orionis. Left panel: H data; right panel: K data. The \((u, v)\) points have been labeled with the interferometer and the baseline used.

Fig. 2. Calibrated squared visibilities of FU Orionis as function of hour angle in H (left column) and K band (right column). Rows from top to bottom display data obtained with the 6 interferometric baselines.

Detection of Planets in Discs Through IR Interferometry (Cambridge, July 2006)  
Malbet et al. (2005)
Fig. 3. Accretion disk model with baseline-averaged data corresponding to parameters listed in Table 4. Lines correspond to the model and symbols to measurements. The dotted line corresponds to an unresolved object. For the sake of clarity, data have been binned in the figure, but the model fit was performed using individual measurements. Top-left panel: spectral energy distribution and best fit model. Right panel: visibility data versus hour angle in $H$ and $K$. Bottom-left panel: synthetic images in $H$ and $K$ in logarithmic scale. East is left and North is up.

Malbet et al. (2005)
FU Ori: quality of the fit

- SED or $V^2$ not sufficient to constrain the parameters
- Global fit has been performed successfully

Malbet et al. (2005)
FU Ori: a faint point source to interpret the wiggling of the PTI/NS data

Malbet et al. (2005)
**FU Ori: nature of the faint unresolved source?**

**Table 6.** Parameters of the best model fit of the location of the spot in 1998, 1999, 2000, and 2003, and its quality.

| Year | $d_{\text{spot}}$ (AU) | $\theta_{\text{spot}}$ (deg) | $\chi^2$ (total) | $\chi^2$ ($|V|^2$) |
|------|------------------------|-------------------------------|------------------|---------------------|
| 1998 | 8.0 ± 1.9              | −48.0 ± 3.3                   | 0.63             | 0.54                |
| 1999 | 9.6 ± 1.5              | −49.4 ± 2.2                   | 0.95             | 0.78                |
| 2000 | 10.1 ± 0.6             | −50.3 ± 1.6                   | 1.04             | 0.91                |
| 2003 | 11.1 ± 0.3             | −49.9 ± 1.7                   | 2.54             | 4.02                |

- Binary companion which triggered the FU Ori outburst?
- Hot spot in the disc?
- Signature of a protoplanet?

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Malbet et al. (2005)
Hot bubble around a protoplanet?

Klahr & Kley (2005)
AB Aur Disc observed by IOTA

A Closure Phase Mystery
(Millan-Gabet et al. 2006)

Grady et al. 1999
AB Aur Results

Long Baselines -> zero closure phase
Point-Symmetric on scales of 4-10 milliarcseconds

Short Baselines -> non-zero closure phase
Asymmetric on scales of 10-50 milliarcseconds
4 degrees CP corresponds to ~7% asymmetry

What could this be?
Detection of Planets in Discs Through IR Interferometry

Millan-Gabet et al. (2005)
Triangle w/ Shortest Baselines

Millan-Gabet et al. (2005)
What interferometry won’t tell us:

What is the physical cause of this localized, bright emission?

Table 1. Results from Fitting to “Disk Hot Spot” Model

<table>
<thead>
<tr>
<th>Model Description</th>
<th>Fraction of Light</th>
<th>Disk Properties</th>
<th>Spot Properties</th>
<th>Reduced $\chi^2$ (V$^2$,CP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unresolved hot spot</td>
<td>0.3</td>
<td>0.68</td>
<td>Ring Diameter 3.6 mas</td>
<td>1.5</td>
</tr>
<tr>
<td>with non-skewed disk</td>
<td></td>
<td>0.02</td>
<td>Ring Width/Diameter 0.25</td>
<td></td>
</tr>
<tr>
<td>Gaussian hot spot</td>
<td>0.3</td>
<td>0.62</td>
<td>Ring Diameter 3.1 mas</td>
<td>1.8</td>
</tr>
<tr>
<td>with skewed disk</td>
<td></td>
<td>0.08</td>
<td>Ring Width/Diameter 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max Skew=1.0 at PA 172°</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Unresolved Spot</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$r_G = 9$ mas at PA 22°</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gaussian FWHM 12 mas</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$r_G = 29$ mas at PA 12°</td>
<td></td>
</tr>
</tbody>
</table>
Prospective

• Detecting unresolved faint companion requires dense $(u,v)$ coverage $\rightarrow$ time consuming

• Spectrally dispersed observations is an efficient way to detect features in discs

• Ideally interferometric imaging will definitively answer to the question of the nature of these bright spots

• Coming interferometric spectro-imagers:
  – VLTI 2nd generation instruments: VSI and MATISSE
  – CHARA and MROI
Planetary gaps in discs with PEGASE & DARWIN
Disk-planet interaction

- Spiral density waves
- Migration phenomena

Gap opening in the disk

Indicator for the presence of a giant protoplanet

Numerical simulations using the code FARGO

(Lin et al.; Kley et al.)

(Masset, 2000, A&A)
### PEGASE & DARWIN

<table>
<thead>
<tr>
<th></th>
<th>PEGASE</th>
<th>DARWIN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectral coverage</strong></td>
<td>2.5-5 µm</td>
<td>6-20 µm</td>
</tr>
<tr>
<td><strong>Spectral resolution</strong></td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td><strong>Angular resolution</strong></td>
<td>→ ~0.3 mas (B=500m, λ=2.5 µm)</td>
<td>→ ~0.9 mas (B=500m, λ=6 µm)</td>
</tr>
</tbody>
</table>

Herwats & Malbet (2005)

Detection of Planets in Discs Through IR Interferometry (Cambridge, July 2006)
Simple gap model in a standard accretion disc

Gap parameters:
- \( d \): distance to the star
- \( l \): gap width

Herwats & Malbet (2005)
Detection criteria: visibility difference

FUOr @5 µm with a gap at 0.25 AU from the star

Herwats & Malbet (2005)
Gap detectability

λ = 3 µm

λ = 5 µm

T Tauri

Herwats & Malbet (2005)
Gap detectability by spectro-interferometry

T Tauri

Baseline=100m

Baseline=200m

Baseline=500m

Wavelength (µm)

Visibility

Wavelength (µm)

Visibility

Wavelength (µm)

Visibility

No gap

Gap at 0.5 AU

Gap at 1 AU

Gap at 3 AU

Herwats & Malbet (2005)
## Requirements for gap detection

<table>
<thead>
<tr>
<th></th>
<th>PEGASE</th>
<th>DARWIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visibility measurement accuracy</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Baselines</td>
<td>200 - 500 m</td>
<td>200 – 500 m</td>
</tr>
<tr>
<td>Gap detectability by spectro-interferometry</td>
<td>0.25 → 2 AU</td>
<td>0.5 → 8-12 AU</td>
</tr>
</tbody>
</table>

Herwats & Malbet (2005)
More realistic models

\[ \frac{\Sigma}{\Sigma_0} \]

\( \lambda \) (µm)

Baseline=500 m

Visibility

Radius (AU)

Varnière et al. (2005); Crida et al. (2005)

Pinte et al. (2006)
Prospects for gap detection

• Planetary gaps seem to be detectable with space interferometers
  – Constructive interferometry
  – Spectral resolution required
  – Long baseline (200 → 500m)

• Complementary to ALMA (Wolf et al.)

• Non-nulling interferometric mode allows also to carry interesting science

• Need to develop scientific tools to help extracting gap signatures out of spectral dispersed visibilities

• Tool to challenge planet formation theories
Summary

• IR long baseline interferometry can bring evidence for presence of planets around stars and in discs.

• Direct detection of exoplanets around main sequence stars is in progress.

• Observations of FU Ori and AB Aur may suggest we already see sites of planet formation in disc. Importance of imaging with interferometers.

• Planetary gaps as exoplanet signatures are observable with space-based IR interferometers like PEGASE or DARWIN.