Measuring the masses of the habitable planets around the 50 closest solar-type stars with Theia

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Pathways 2015: Pathways toward habitable planets – 16/07/2015

Acknowledgments:
Astrometry on the host star: principle of the detection

Principle of the astrometric detection:
The gravitational pull of the planets causes the stars to orbit around the center of mass of the system (star + planets)

\[ A = 3 \mu \text{as} \times \frac{M_{\text{planet}}}{M_{\text{Earth}}} \times \left( \frac{M_{\text{star}}}{M_{\odot}} \right)^{-1} \times \frac{R(\text{AU})}{1 \text{AU}} \times \left( \frac{D(\text{pc})}{1 \text{pc}} \right)^{-1} \]

A few hundred stars (~50 MS FGK)

Observations
- “Double blind” tests:
  Traub et al. (2009)
  Anglada et al. (2014)
- Stellar noise not an issue
  Lagrange et al. (2011)

Sun diameter

The Solar System

The Sun Orbit

~ distance to nearest star

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Jupiter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 pc</td>
<td>3 \mu as</td>
<td>5 mas</td>
</tr>
<tr>
<td>10 pc</td>
<td>0.3 \mu as</td>
<td>0.5 mas</td>
</tr>
</tbody>
</table>

Astrometric signatures:
Precision differential astrometry

**Differential astrometry**: measurement of the position of an object compared to other ones located in the field.

**Field of view**: approx 0.5 deg

**Precision**: 0.3 µas <-> ~1e-6 the PSF width <-> 5e-6 pixel

**Pointed astrometry** allows to increase the exposure for faint objects, but reduces the number of targets.

**Number of visits**: ~100 per target star

Field of View
Science targets: our close galactic neighbourhood

We hardly know our neighbours!

Need for astrobiology:
- **spectroscopic characterization**
- **not only around M stars!**
  - terrestrial planets (<10 M$_\oplus$)
  - in habitable zone
  - around close Sun-like main sequence stars (<10 pc)
  ➞ only ~50 FGK main sequence targets

Current limitations:
- Transits: few close targets (geometric probability)
- RVs: Stellar noise. Possible around M stars. Very hard for Solar-like stars

We expect many more existing planets
[Howard, 2012]

The Solar neighbourhood: only about 9% of stars have known exoplanet(s)
Astrometry and RV: period-mass parameter space

Known exoplanets in 2014

- Transits
- Radial velocities
- Imaging or interferometry
- Microlensing
- Astrometry
- Pulsar

RV are needed to complement astrometry on massive long period planets.

Theia search space

- Theia mission duration (3 years, maximum sensitivity)

Pathways 2015: Pathways toward habitable planets – 16/07/2015 - Theia
Precise mass measurement

Mission optimization

- Astrophysical sources of false positives:
  - Background stars
  - Zodical dust clouds

- Ambiguities between planets because of projection effect

- Planets orbits can be partially into IWA

Synergy with direct imaging (why not just image first?)

Planet1:
- Orbit
- Mass

Planet2:
- Orbit
- Mass

Planet3:
- Orbit
- Mass

Ah! Here's the potentially habitable planet

Image from High Contrast Imaging Testbed. Credit: NASA/JPL-Caltech
NEAT concept (M3 proposal)  
Malbet et al. (2014)

Telescope spacecraft

Metrology

Telescope axis beam

Detector spacecraft

Dynamical Young’s interference fringes

λ/D ~ 130 mas ~ 2 pixels of 10 μm  
0.1 μm as ~ 10⁻⁶ pixel accuracy ~ 10 pm
Theia concept (M4 proposal)

λ / D ~ 160 mas ~ 2 pixels of 10 μm
1 μ as ~ 6.10^{-6} pixel accuracy
Theia - mission parameters & ESA evaluation

- **Mission parameters:**
  - 3 year mission
  - Ø 0.8m primary mirror (Ø 1m for NEAT)
  - L2 orbit
  - M4 cost envelop (450M€)
  - Multipurpose “observatory”: dark matter (34%), nearby Earths (17%), compact objects (11%), Gaia follow-up (11%), open time (15%)
  - Main science case: **dark matter, detection of DM clumps**
    -> constraining the nature of dark matter

- **ESA feedback:**
  - Positive progression NEAT -> Theia
  - Main ESA red flag: budget and programmatic
  - Different CNES and ESA cost estimations (420M€ vs 546M€)
Expected detection thresholds of Theia

Main assumption: photon noise limited with Theia (0.5 FoV, Ø 0.8m)

Only 2600 hours, ie. 10% of 3 years (7% used for RV follow-up)

Time distributed equally around the 50 easiest (~closest and Sun like) stars
Expected exoplanet yield of Theia (‘‘accounting for the \( \eta_{\text{earth}} \) factor’’)

- Model based on Theia error budget & extrapolated Kepler distribution
  [Traub 2015]
  [Priv. comm., Traub & Crouzier]
- Statistical conversion Mass <-> radius
- Hard cutoff @ \( P = 3 \) years
- 6 categories: cold/HZ/hot and Terrestrial/Gaseous
- In average 6/14 potentially habitable planets detected
DICE (Detector Interferometric Calibration Experiment)
Crouzier et al. 2014

• An experiment to demonstrate CCD calibration for astrometry at a precision of 10 μpixel (~1μas with the Theia design)

• Optical configuration imitates NEAT

• Poster #66469 (Crouzier et al.)

The Detector Interferometric Calibration Experiment
DICE (Detector Interferometric Calibration Experiment)

- Metrology bench
- Coherent monochromatic light source
- Translation stage
- Light detector
- Single mode fibers
- Metrology baseline
- Mirror
- Pseudo stars (object plane)
- Vacuum chamber
- Optical bench
- White light source
- Zerodur bench
- Metrology fibers
- Invar bench
- Liquid core fiber
- Peltier
- CCD

- Fiber support
- Baffle
- Translation stage
- Water cooling

- Pinhole mask support

- Mirror/diaphragm

- Metrology fiber holders

- DICE (Detector Interferometric Calibration Experiment)

- Metrology (Moving young fringes)

- Pseudo stars

- Centroid common motion
DICE: experimental results

Improvement by:
- Use of jittering techniques
- Better stray light control

Calibrations:
- Pixel QE map
- Pixel positions*

Regular grid

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<thead>
<tr>
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<th>No flat</th>
<th>flat</th>
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</thead>
<tbody>
<tr>
<td>No metrology</td>
<td>$3.6 \pm 0.59 \times 10^{-4}$</td>
<td>$2.8 \pm 0.45 \times 10^{-4}$ (goal : $1e-5$)</td>
</tr>
<tr>
<td>Metrology</td>
<td>$5.9 \pm 0.94 \times 10^{-4}$</td>
<td>$4.3 \pm 0.69 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

* map

Stray light!
Conclusion

- A specific need still not addressed: measure the masses of HZ planets around nearby Sun-like stars
- Evolving concept, astrometry with diverse science cases, becoming closer to selection
- Improved instrument concept and performances
- Ongoing instrumentation efforts for detector calibration and optical stabilization + calibration (IPAG & JPL)

Thank you for your attention!