Detection and Characterization of Extra-Solar Planets

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Exploring the Cosmic Frontiers

European Space Agency
Planet Detection Methods


[corrections or suggestions please to michael.perryman@esa.int]

Planet Detection Methods

- Accretion on star
- Self-acreting planetesimals
- Magnetic superflares
- Radio emission
- Reflected light
- Imaging
- Space
- Ground
- Ground (adaptive optics)
- Imaging/spectroscopy
- Resolved imaging
- Timing residuals
- Detection of Life?
- Ground

Existing capability
Projected (10-20 yr)
Primary detections
Follow-up detections
n = systems; ? = uncertain

- Photometric signal
- Timing (ground)
- Radio
- Optical
- Astrometric
- Space interferometry (infrared/optical)
- Disks
- Free-floating detection
- Observing
- Imaging
- Space
- Ground

- Detectable planet mass
- Pulsars
- Binary eclipses
- White dwarfs
- Radial velocity
- Magnetic superflares
- Photometric
- Astrometric
- Space
- Detection (ground)
- Timing

10M_J

M_J

10M_E

M_E

122 planets (107 systems, of which 13 multiple)

- 2
- 1
- 3
- 1?
- OGLE P<2 days
What will not be covered...

• Observations of protostellar disks, formation, evolution, migration, stability, etc
• Review of ground-based surveys:
  – radial velocity: 15 ongoing 3 planned
  – transit: 13 2
  – micro-lensing: 5 -
  – imaging (detection): 2 8
  – radio: 2 (+ pulsar) -
  – astrometry: 1 2
• Space observations by HST, Spitzer, JWST
• Capabilities of OWL/ELT (see talk by Hainaut)
Detection domains:
- radial velocities
- astrometry
- transits

- Not shown:
  - imaging/detection
  - lensing

These address different types of objects, with at least two different goals: formation; habitability
Kepler (NASA)

Method:
- high precision, long-duration photometry
- 1 m telescope, 12° field
- $10^5$ main sequence stars, V<14 mag

Objectives:
- photometric transits for Earth-like objects

Results:
- terrestrial inner-orbit transits:
  - 50/185/640 with $R \sim 1.0/1.3/2.2 \, R_{\text{Earth}}$
- giant inner planets from reflected light:
  - $\sim 870$ planets with $P < 1$ week
- giant planet transits:
  - 135 inner-orbit planets + 30 outer orbit

To note:
- sensitive to acceptable S/N
- monochromatic observations

Launch: Oct 2007

http://www.kepler.arc.nasa.gov/

MOST: launched June 2003, 15cm
  (‘working beautifully’, results soon…)
COROT: launch planned June 2006
HST bulge: Sahu 100-200 expected
Eddington (ESA)

Method:
• high precision, long-duration photometry
• 1.2 m telescope, 3° field
• $5 \times 10^5$ stars, V<18 mag

Objectives:
• asteroseismology + photometric transits

Results:
• 20,000 planets with $R < 15 R_{\text{Earth}}$
• 2000 terrestrial planets
• dozens of Earth-like planets

Launch: TBC

http://www.rssd.esa.int/Eddington

• Approved: 2002
• Cancelled: Nov 2003
• Studies continue in context of future options
Transits of habitable Earths

Physical diagnostics of HD 209458:
• detection of sodium (Charbonneau et al 2003)
• extended hydrogen exosphere (Vidal-Madjar et al 2003)
• detection of O and C (Vidal-Madjar et al 2004)
• search for CO (Brown et al 2002, Deming et al); water (Rojo et al)
Gaia (ESA)

Method:
- astrometry, Hipparcos principles
- two $1.4 \times 0.5 \, \text{m}^2$ mirrors + CCDs
- continuous ‘revolving’ sky scanning
- 5-year observations: 100 epochs per star

Objectives:
- distances + motions for $10^9$ stars
- 10-20 microarcsec at 15 mag
- structure and evolution of Galaxy

Launch: 2010
http://www.rssd.esa.int/GAIA
Gaia: Planet motions

\[ \mu \sim 250 \text{ milliarcsec/year} \]
\[ \pi \sim 100 \text{ milliarcsec} \]

Single star

Planète : \( \rho = 100 \text{ mas} \) \( P = 2.5 \text{ ans} \)

Planète : \( \rho = 100 \text{ mas} \) \( P = 18 \text{ mois} \)
\[ \alpha = \left( \frac{M_p}{M_s} \right) \left( \frac{a_p}{d} \right) \]

...\( \alpha \) in arcsec if \( a \) in AU and \( d \) in pc

At 10 pc:
- Jupiter: 500 \( \mu \)arcsec
- 10 Earth: 3 \( \mu \)arcsec
- Earth: 0.3 \( \mu \)arcsec
Gaia: Expected Astrometric Discoveries

- **Survey to 150–200 pc:**
  - complete census of all stellar types; periods in range 2–9 years
  - primarily sensitive to Jupiter-type systems

- **Large-scale detection and physical characterisation:**
  - detection of 20–30,000 planetary systems
  - masses, rather than lower limits ($M \times \sin i$)
  - orbits for $\approx$5000 systems + multiple systems: relative inclinations
  - mass down to $10 M_{\text{Earth}}$ to 10 pc

- **Photometric events:**
  - transits: $\sim$4000 ‘hot-Jupiters’ possible
SIM (NASA)

Mission:
• pointed interferometer
• baseline: 10 m

Objectives:
• astrometric detection
• 1-4 microarcsec to 20 mag
• survey: thousands of stars
• detailed orbits
• planet programmes:
  • 50 epochs × 1 hour each
  • 250 stars at 1 microarcsec
  • 2000 stars at 4 microarcsec

Launch: 2009
GEST

- microlensing
- 1.5 m aperture
- 1.25° field
- targets: $10^8$ distant, bulge main-sequence stars

Objectives:
- ~100 Mars-Earth mass between 0.7-10 AU
- free-floaters (if by-products of formation)
- 50,000 giant planets via transits

Status: not selected in 2002 Discovery, but re-proposal expected in 2004
BOSS (and UMBRAS, CORVET, NOME)

**Concept: Big Occulting Steerable Satellite**
- e.g. 70×70 m² occulting screen
- solar sailing + ion/chemical propulsion
- e.g. used in conjunction with JWST at L2
- but: TPF focusing on interferometry/coronography

**Results (C&S 2000):**
- 2×2 arcsec² ‘solar systems’
- λ = 1 µm
- 8m telescope, t = 3000s
- separations of 0.1–0.2 arcsec
- 10⁻⁹ at 8 mag

Venus/Earth at 3 pc  
Jupiter/Saturn at 10pc
Biomarkers: a synopsis

- terrestrial atmospheres: degassing
- transition to life: ~ 4 billion years ago
- photosynthetic cyanobacteria: ~ 2 by

\[
\text{CO}_2 + H^+ \rightarrow \text{organics} + O_2
\]

photosynthesis

760 nm tracer
(but Earth O_2-free until -2 Gyr)

- anaerobic decomposition of organics; combines with O_2

O_3 (O_2 tracer): 9.6 µm
H_2O: 6-8 µm
CH_4: 7.7 µm (or shorter)
CO_2: 15 µm

Absence of O_2 ≠ absence of life
Simultaneous detection of CH_4 + O_2 ⇒ life?
Simultaneous detection of H_2O + O_3 ⇒ photosynthesis?
Detection of vegetation signature?
Characterizing Earths

Calculated atmospheric spectra ($\lambda/\Delta\lambda = 200$)

Observed spectra

**TPF** (NASA)

Mission (pre-March 2004):
- instrument choice:
  - IR interferometer ($40m^2$), or…
  - optical coronograph
- scientific choice: reflected or thermal

Objectives:
- direct detection of planetary systems
- spectroscopy indicating life
- ozone at 25pc: 2-8 weeks/object

April 2004: NASA announcement:
- $6 \times 3.5m$ visual coronograph in 2014:
  - 32 nearby stars full search
  - 130 stars incomplete search
    (low $p$(Earth), but good for Jupiters)
- ESA collaboration for full mission

Launch:
- precursor (TPF-C): 2014
- free-flying interferometer: <2020
**Darwin** (ESA)

**Method:**
- 20–80 m baseline mid-IR interferometer
- 4 × 2.5 m (was 6 × 1.5) telescopes
- star/planet intensity: $10^6$–$10^9$

**Objectives:**
- direct detection
- are Earth-like planets common?
- how do they form?
- detect tracers of life in mid-infrared

**Precursors:**
- GENIE (ongoing): VLTI nulling interferometer
  - technical precursor, using UTs or ATs, $L=3.6\mu m$
  - required for pre-launch study of Darwin targets
  - to ESA/ESO 5-7 May, ESO Council late 2004
- SMART-3 (not yet approved): demonstration of formation flying for 2 spacecraft (Darwin/XEUS)

Launch: 2015?
Darwin/TPF detection (Mennesson & Marrioti 1997)

- Venus
- Central star ‘nulled’
- Mars
- Earth

\[ d = 10 \text{ pc} \]
\[ t = 60 \text{ hr} \]
Interferometry vs Coronography

• Science aspect:
  – is reflected (optical or near IR) or thermal (mid-IR) best to characterise planets (albedo, colour, temperature)?

• Instrumental aspect:
  – is an interferometer or coronagraph the ‘best’?

• NASA technology plan for TPF:
  – “Technology readiness, rather than a scientific preference for any wavelength region, will probably be the determining factor in the selection of a final architecture”

• ESA effort (Darwin) is focused on an interferometer

• Many idea for precursors to TPF, especially in US:
  – which are scientifically driven, decoupled from long-term technology?
  – which are mandatory technology precursors?
Unapproved TPF ‘precursors’: missions/concepts

- **Eclipse**: (Trauger et al. 2003) – 2004 Discovery?
  - 1.8 m + coronograph + wavefront correction – Jupiters to 5 AU for stars to 15 pc

- **JPF**: Jovian planet finder (Clampin et al. 2002) – 2004 Discovery?
  - 1.5 m + coronograph, originally on ISS – Jupiters to 2-20 AU

- **ESPI**: Extrasolar planet imager, Midex, (Lyon et al. 2003)
  - 1.5×1.5 m apodized square aperture – Jupiters around 160 stars to 16 pc

- **ExPO**: Extrasolar planet observatory (Gezari et al. 2003)
  - similar concept to ESPI proposed as Discovery class mission

- **SPF**: Self-luminous planet finder (Woolf et al. 2001)
  - search for younger/more massive Jupiters in Jupiter orbits

- **FKSI**: Fourier-Kelvin stellar interferometer (Danchi et al. 2003)
  - mid-infrared nulling interferometer: detection of 25 EGPs within 10 pc

- **OPD**: Optical planet discoverer (Mennesson et al. 2003)
  - midway between coronography and Bracewell nulling

- **PIAA**: Phase-induced amplitude apodization (Guyon 2003)
  - reflection of an unapodized flat wavefront on two shaped mirrors
Detection capabilities: Earth at 10pc (Angel 2003) 
[Δθ=0.1 arcsec, t=24 hr, QE=0.2, Δλ/λ=0.2]

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Size</th>
<th>λ (µm)</th>
<th>Mode</th>
<th>S/N</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Darwin/TPF-I</td>
<td>4 × 2 m</td>
<td>11</td>
<td>N</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>TPF-C</td>
<td>3.5 m</td>
<td>0.5</td>
<td>C</td>
<td>11</td>
<td>Typical launcher fairing diameter</td>
</tr>
<tr>
<td></td>
<td>7 m</td>
<td>0.8</td>
<td>C</td>
<td>5–34</td>
<td></td>
</tr>
<tr>
<td>Antarctic</td>
<td>21 m</td>
<td>11</td>
<td>N</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8</td>
<td>C</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>CELT, GMT</td>
<td>30 m</td>
<td>11</td>
<td>N</td>
<td>0.3</td>
<td>30m too small at 11 µm with coronograph</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8</td>
<td>C</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>OWL</td>
<td>100 m</td>
<td>11</td>
<td>C</td>
<td>4</td>
<td>Large Φ for IR coronographic suppression</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8</td>
<td>C</td>
<td>46</td>
<td>Optical spectroscopy possible</td>
</tr>
<tr>
<td>Antarctic OWL</td>
<td>100 m</td>
<td>11</td>
<td>C</td>
<td>17</td>
<td>Comparable to Darwin/TPF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8</td>
<td>C</td>
<td>90</td>
<td>Water bands at 1.1 and 1.4 µm feasible</td>
</tr>
</tbody>
</table>

Background = thermal, zodiacal (unknown density), stellar
N = null, C = coronograph
Ground results assume long-term average, fast atmospheric correction
NASA’s Origins development

First Generation
- Kepler
- SIM
- JWST
- SIRTF
- SOFIA
- Enabling Technology

Second Generation
- TPF
- Life Finder
- Large UV / Optical Observatory

Visions
- Planet Imager
Life Finder

Objectives: confirm evidence of life revealed by TPF/Darwin (e.g. oxygen/methane or ‘vegetation signature’). Targets are as faint as HDF galaxies, in star glare at 0.1 arcsec

Developments needed:
• lower mass, better wavefront optics
• pointing/sunshield/vibration damping
• cooling, orbit control
• space assembly: costs $\propto D^3$

Requirements (how big is needed?):
• for 7.6 $\mu$m methane (50m$^2$ for TPF):
  • $220 \text{ m}^2 \ (5 \times 8\text{m})$ at $d = 3.5 \text{ pc}$
  • $4000 \text{ m}^2 \ (80 \times 8\text{m})$ at only $d = 15 \text{ pc}$

Mini Life Finder (Woolf et al 2001)
50 x 10 m$^2$, 10 tons (optics+structure)

http://www.niac.usra.edu
Methane
Moon
OH Airglow

Wavelength (angstroms)

15095 15830 16692
Labeyrie (1999):
- 150 × 3 m diameter mirrors over 150 km
- densified free-flying ‘hypertelescope’
- detect Amazon ‘green spots’ at 3 pc

Densified exit pupil: exit pupil has sub-pupils with larger relative size than sub-apertures in the entrance pupil

Simulations (Riaud et al 2002):
- 37 × 60 cm infrared telescopes
- baseline = 80 m
- 389 M5-F0 stars < 25 pc
- zodiacal + exo-zodiacal light
- 10-hour ‘snapshots’

Results:
- Earth-like planet detected around 73%

Ground-based imaging:
- Carlina (OVLA-type)
- VIDA: densified pupils on VLTI
- ALIRA: Atacama large IR array
- Antarctic Plateau Interferometer
Earth Imager: imaging of Earth-type planets

- **Bender & Stebbins (1996):**
  - $10 \times 10$ resolution elements across ‘Earth’ at 10 pc:
    - 15–25 spacecraft (telescopes) each of 10 m diameter, spread over 200 km
    - image reconstruction uncertainties (rotation, variable cloud cover, etc)
  - Cho & Seager 2004: large-scale atmospheric flow, coupling of
    land and ocean, and implications for habitability
  - $100 \times 100$ resolution elements:
    - 150–200 spacecraft distributed over 2000 km, integration time: 10 years

- **Labeyrie et al. (1999)**
  - Epicurus: extra-solar earth imager, submitted to ESA F2/F3 AO

- **Woolf et al (2001):**
  - ~50-100 Life Finders, operating in an interferometric array

- **The consensus:**
  - ‘daunting’, ‘monstrously difficult’, ‘unjustifiable’
  - costs: 50-100 $\times (>>$2 billion), ‘dwarfing Apollo’
Nanoarcsec
Astrometry

Earth at 100pc: 30 nas
Mission: 10 nas

σ ∝ D^{-3/2} × H^{-1/2}
⇒ 50m × 10m aperture
⇒ focal length: 1600m
Schedule


Corot  Eddington  Kepler

Gaia  SIM

TPF-C  TPF/Darwin

Very large telescopes (CELT, OWL)

Very large space arrays

Europe  US
Summary

• Statistics – formation & habitability (2008-2012):
  – Kepler/[Eddington]: several thousand, several hundred habitable zone
  – Gaia: astrometry: ~ 20,000 Jupiters (P~years) + 5000 photometric
  – [GEST]: lensing + transits, including free-floating planets

• Detection (‘imaging’) of specific systems (2015-20):
  – TPF/Darwin: few Earths in habitable zone to 20–30 pc

• Distant Visions:
  – Life Finder (confirmation of life): ‘very challenging’
  – Planet Imager (resolving surface): ‘monstrously difficult’
END