Recognizing and characterizing terrestrial exoplanets

Pathways towards habitable planets II
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And thanks to the entire Exo-S team!
Kuchner, S. Shaklan & JPL design team
Where’s the planet?

ε Eridani

HST ACS/WFC

200×200 arcsec
Where’s the planet?

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Box 30 ×20 arcsec
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Where’s the planet?

Hubble Extreme Deep Field (Illingworth et al 2013) \(\sim 10^6\)s total

HST ACS/WFC

F606W 174ks

Box 30 \(\times\)20 arcsec
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F606W 174ks

Box 30 \(\times\) 20 arcsec

30\(^{th}\) mag object

Circle radius 1 arcsec
Extragalactic Background

The deepest part of the XDF has a limiting magnitude near $V \sim 31$.

7,121 galaxies above the 5-sigma significance level in $\sim 4.7$ arcmin$^2$.

Significant image crowding at $V \sim 30$, where 45% of the pixels contain galaxy light (Koekemoer et al. 2013).

Faint extragalactic sources appear unresolved.

Other surveys (e.g. Windhorst et al. 2011) indicate we should expect a few dozen galaxies per arcmin$^2$ at $V < 25$: brighter, extended, galaxies will make planet detection difficult wherever they dominate the FOV.

1 arcmin$^2$ field from the Hubble XFD Extreme Deep Field (Illingworth et al. 2013).
Galactic Stars
Galactic Stars

For Galactic latitudes above 30° (or below -30°) the probability of a contamination by a galactic star is less than 1%

However, at all galactic latitudes, the probability remains greater than $10^{-3}$

Within 10° of the galactic plane, the probability of finding a Galactic star in 1 arcsec$^2$ is >10%.

Almost one third, 26/96, of the Rendezvous target sample is within 10° of the galactic plane.


Contamination $\approx 10\%$ at $b \approx 10°$
Mitigation: in motion, sooner rather than later

Proper motion: Proper motion can discriminate between planets and background objects for all in sample after a year.

Parallax: about half the sample have easily measured parallax (~1-6 month but may not be compatible with mission constraints)

Orbital motion: Earth analog potentially detectable to 20 pc in 1 month (30° orbital longitude change). A significant but unknown, number of planets are likely to exhibit detectable orbital motion within a month.

For the majority of the highest priority targets, confirmation of a planet candidate can be done after a month or less using either common proper motion, parallax, or both

Red lines: Rendezvous (WFIRST+starshade): limit after one month

Blue lines: 1-m Exo-S
Mitigation: photometric

Colour-magnitude (B-V) & V

Stars red, galaxies blue

Earth (green), colours change due to diurnal rotation, cloud, phase

> Planets are unremarkable in conventional colour/magnitude systems

IFU allows post-facto definition of photometric bandpasses

Colour-colour (B-V) & (V-R)

Post-facto colour indices (example):
(450–625) vs (875–950): clean separation of planets

Besançon model of the Galaxy $l=0^\circ$ $b=10^\circ$; s
http://model.obs-besancon.fr/
CANDELS GOODS-S extragalactic source
Mitigation: polarimetric

Planets shining by scattered light of host star are expected to be polarized – few to tens %

- The density of background polarized sources is not known, but certainly much lower than the density of all background sources. P.A. within 5° of tangent vector, reduces additional 18×

- Uncertainty on polarization % scales with the SNR, uncertainty on P.A. scales with product of polarization and SNR (Miller, Robinson & Goodrich 1987)

- P.A. uncertainty 10°, requires 3σ detection of polarization degree leading to source 4–8 × brighter than faintest detection (assuming 5σ flux detection limit).

Hence polarimetry candidate detection (PDI) & identification can be applied to planets which are modestly brighter than the faintest detectable*

*For polarimetric detection the entire spectrum can be used; hence improvement by about a factor 2 in favorable circumstances
Advantages of including polarization spectroscopy

**Mission design:**
- Wavefront correction
- **Detection - differential method, PDI**
- **Identification of candidates without revisit**
- **Geometry - exozodi disks**
- **Characterization**

*Beware! polarization affecting appearance of spectrum*
*everything is scattered light, could be polarized ~50%*

**Characterization includes:**
- Rayleigh scattering in atmosphere
- Surfaces, ices, rock, oceans, cirrus, clouds
  - Seager 2000; Stam et al 2004; Marley & Sengupta 2011 – giant planets

Remote sensing of **liquids**
- Specular reflection from **oceans**; glint. Max P% Brewster’s angle.
  - For Earth, brightness significant near crescent (Robinson et al 2011, 2014)
  - Cloud-free **ocean world, glint dominates**, high P% (Williams & Gaidos 2008).
- **Rainbows**: aerosols; clouds
  - Classic Venus analysis, sulfuric acid rainbow Hansen & Hovenier 1974
  - See also Bailey 2007; Karalidi et al 2011

*Peak rainbow phase angle versus refractive index (Bailey 2007)*
A simple strategy: accept what is there

Observe for a predetermined integration time

- **useful S/N on Earth twin** \( \Rightarrow \) **large aperture telescope**

**High contrast suppression system** (coronagraph or starshade) with:

- **Integral Field Spectrograph**
  - **Spectra of all sources in field**
    - no concerns over “choosing”, or acquisition, multiple systems the norm
  - **Post-facto band definition/PCA**
  - **Speckle discrimination (some architectures)**

include polarization capability

- **Detection**
- **Identification**
- **Geometry**
- **Additional characterization**

Simple option:

- Just observe every target star for predetermined time - unbiased inventory of local planetary demographics
- Revisit most interesting

Examples: above Kasdin et al left: Rodenhuis (2011) in Polarimetry with Extremely Large Telescopes
Conclusions

- The problem and probabilities
  - Galactic
  - Extragalactic

- Solutions:
  - Proper motion, parallax, orbital motion
  - Post facto spectroscopy/photometry/PCA
  - Polarimetry

- Instrumentation can affect mission design
  - IFU, polarimetry
    - Take inventory of local neighborhood
  - Lets not skimp on the instrumentation
    - *Do we really need $10^{-10}$ suppression?*

- Need photons, S/N – large telescope – to do it right: identification, photometry, spectroscopy, timing, polarimetry

- *Advert: HST GO/AR-14320* Characterizing the Galactic and Extragalactic Background of Exoplanet Direct Imaging Targets P.I. M. Turnbull