Requirements for Imaging and Spectroscopy of Habitable Earths

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OSIRIS-Rex **optical** spectrum
- Evidence of gas-phase H$_2$O over the entire planet.
- Substantial concentration of O$_2$.

OSIRIS-Rex **infrared** spectrum
- Evidence of CO$_2$, O$_3$, CH$_4$, and H$_2$O.
- Atmosphere transparent between 8.3 and 12.5 μm (probe of surface temperatures).

Lauretta et al. 2018
*Credit: NASA/Goddard/University of Arizona/Arizona State*
Scientific motivation

Are we alone in the Universe? Do other life-bearing planets exist? How common is Earth? Where is everyone?

Galileo observations of Earth: large amount of O\textsubscript{2} and traces of CH\textsubscript{4} considered as indicator for life (Sagan 1993)
Scientific goals

Ambitious/extraordinary endeavors can be broken in intermediate science goals:

Goal 1: Determine the overall architectures of a sample of nearby planetary systems.

Goal 2: Determine or constrain the atmospheric compositions of discovered planets.

Goal 3: Determine or constrain planetary radii and masses.

Understanding planet atmospheric processes and their evolutionary histories is crucial for unambiguously identifying extraterrestrial life.
Science goals

Goal 1: Determine the overall architectures of a sample of nearby planetary systems. Why huge diversity? Formation and evolution processes? Interaction/correlation with star and dust belts? Typical planet architectures? How common is the solar system?

OBSERVING NEARBY STARS IS REQUIRED IN ORDER TO GET THE COMPLETE PICTURE!
Science goals

Goal 2: Determine or constrain the atmospheric compositions of discovered planets. Understand chemical diversity. Which planets have an atmosphere? Which planets have water on their surface? Which planets have continents and oceans?

Visible to infrared wavelengths rich in atmospheric signatures

Kaltenegger et al. 2017
Science goals

**Goal 2:** Determine or constrain the atmospheric compositions of discovered planets. Understand chemical diversity. Which planets have an atmosphere? Which planets have water on their surface? Which planets have continents and oceans?

<table>
<thead>
<tr>
<th>Species</th>
<th>Information on planet</th>
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</thead>
<tbody>
<tr>
<td>Visible and infrared continuum</td>
<td>Orbital parameters =&gt; dynamical mass</td>
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<tr>
<td>Infrared continuum</td>
<td>Combination of surface temperature, pressure, radius, and albedo</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Presence of an atmosphere</td>
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<tr>
<td>H$_2$O</td>
<td>Presence of water</td>
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<tr>
<td>O$_2$, O$_3$, CH$_4$</td>
<td>Suggestion of life</td>
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</table>

(see complete list with wavelength and bandwidth in SAG15 report)
Science goals

Goal 2: Determine or constrain the atmospheric compositions of discovered planets. Understand chemical diversity.

Is elemental composition correlated to exoplanet provenance or stellar metallicity?

Image credit: G. Tinetti (ARIEL)
Science goals

Goal 3: Determine or constrain planetary radii and masses. Required to break model degeneracies. Ex: gravity vs CH$_4$

Morley et al. 2014
Science goals

- **Goal 3**: Determining or constraining planetary radii and masses. Radius stronger constraint on “rockyness”:

![Graph showing the relationship between planetary mass and radius, with different symbols representing different planets and their compositions.](Kaltenegger et al. 2017)
Summary of science goals (from SAG15)

<table>
<thead>
<tr>
<th>Science Questions and Required Data for Direct Imaging Exoplanet Missions</th>
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<tbody>
<tr>
<td><strong>Science Questions</strong></td>
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<tr>
<td>---------------------------------------------------------------</td>
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<td></td>
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<tr>
<td><strong>B1 Rotation and Obliquity</strong></td>
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<td><strong>B2 Which Rocky Planets have Surface Liquid Water?</strong></td>
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<tr>
<td><strong>B3 Aerosols and Composition in Giant Planets</strong></td>
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<tr>
<td><strong>B4 Terrestrial Planets Atmospheric Composition</strong></td>
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<td><strong>C1 What Processes/Properties Influence Atmospheric Circulation?</strong></td>
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<tr>
<td><strong>C2 Key evolutionary pathways for rocky planets?</strong></td>
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<td></td>
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<tr>
<td><strong>C3 Geological Activity/Interior Processes</strong></td>
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</tbody>
</table>
And then? How to identify life?

- Several important molecules to look for (ex: O$_2$, O$_3$, CH$_4$) but no clear/unambiguous biosignatures (false positives!)
- Necessary to better planet atmospheric processes and their evolutionary histories
- Large sample is required
- Population analysis:

Colour-colour or CH$_4$/O$_2$/H$_2$O diagrams will allow to identify families of planets and maybe some anomaly

Wagner et al. 2016
And then? How to identify life?

Domagal-Goldman et al. 2014
Overview

1. Scientific motivations and goals

2. Level 1 scientific requirements
   - HZ exoplanet occurrence rate
   - Prevalence of exozodiacal dust

3. Mission scientific requirements
   - Detection and spectroscopic characterization
   - Ground-based observations

4. High-level technology requirements
Exoplanet yield

• Obvious impact on the exoplanet yield of any mission design

• Many studies in the literature (e.g., Stark et al. 2015 and 2016, Kammerer and Quand 2018, see Morgan’s talk tomorrow)

• Ex: Stark et al. 2015 and 2016

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![Graph](image-url)

**Starshade (4m, 550nm)**

- ▲ φ = 0.98
- ■ φ = 0.98
- ▼ φ = 0.99

**Corono (10m, 550nm)**

- φ = 0.96
Exoplanet yield

- Obvious impact on the exoplanet yield of any mission design
- Many studies in the literature (e.g., Stark et al. 2016, Kammerer and Quand 2018, see Morgan’s talk tomorrow)
- Ex 2: Léger et al. 2015
Exoplanet occurrence rate

- Vary according to authors

Source: SAG13 report
Kepler field vs nearby stars

Multiple studies agree to ~50% level

Hot Jupiter rate differs by ~3x

Future surveys must plan for 2-3 variations in planet occurrence rate (see SAG13 report)
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Exozodiacal dust – why do we care?

• **Exozodis**: dust in or near the HZ of stars

• **Source of noise and confusion**
  - Solar zodiacal cloud ~300 times brighter than Earth (IR and V)
  - Asymmetric features can mimic the planetary signal.
Direct impact on science yield

Reduce exozodi by 10x, increase yield by ~ 2x
Stark et al., 2014, 2015

Tolerable dust density is ~15 zodis for IR imagers
Defrère et al. 2010
Source of confusion

Defrère et al. 2012
Exozodiacal dust – what do we know?

- New results from LBTI’s HOSTS survey:
  Upper limits on the median HZ dust level of 13 zodis (95% confidence) for a sample of stars without cold dust and 26 zodis when focusing on Sun-like stars without cold dust

Ertel et al. in press
HOSTS status

- **HOSTS survey completed last week (35 total stars observed, ongoing analysis).**

- **More observations required:**
  - Exozodi still major uncertainty in exoplanet yield predictions
  - Some high priority targets (i.e. nearest stars) not observed during baseline survey
  - To tie the phenomenon of zodiacal dust to physical models and proxy markers

- **System performance and robustness will improve (new wavefront sensor, real-time water vapor seeing correction, new optimized data acquisition approach,)**
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Key questions

- What are the **minimum science requirements** to justify an exoplanet direct imaging mission?

- What are the **additional science goals** that can be used as "discriminators" to evaluate science performance beyond the minimum thresholds?

- What are the possible achievements from the ground by plausible launch date, and overlapping the expected mission lifetime?
Minimum science requirements

- List from SAG3 conclusions (non-exhaustive):

  1. Able to detect an Earth twin at quadrature in a Solar System twin at a distance of 10 pc

  2. Able to detect a Jupiter twin at quadrature in a Solar System twin at a distance of 10 pc

  3. Examine at least 14 HZs to detect point sources with the sensitivity to detect terrestrial planets

  4. Characterize every discovered candidate exoplanet by $R \geq 4$ spectroscopy (0.5 µm to ~1.0 µm)

  5. Able to characterize the “Earth” in a Solar System twin at 5 pc and the “Jupiter” in a Solar System twin at 10 pc by $R > 70$ spectroscopy (0.5 µm to ~1.0 µm)

  6. ...
What can be done?

- Exoplanet yield based on Kepler stats:
  - 207 (R < 6R_E) planets observable (V band), 70 (J band), and 38 (H band)
  - No significant improvement with contrasts better than 10^{-10}
  - Improving IWA more important at this point

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>12 m</td>
<td>Aperture size</td>
</tr>
<tr>
<td>IWA</td>
<td>2 \frac{\lambda_{\text{eff}}}{D}</td>
<td>Inner working angle</td>
</tr>
<tr>
<td>C_{\text{ref}}</td>
<td>1e-10</td>
<td>Achievable contrast performance</td>
</tr>
<tr>
<td>\lambda_{\text{cen}, V}</td>
<td>554 nm</td>
<td>Central wavelength of V-band filter</td>
</tr>
<tr>
<td>\lambda_{\text{cen}, J}</td>
<td>1245 nm</td>
<td>Central wavelength of J-band filter</td>
</tr>
<tr>
<td>\lambda_{\text{cen}, H}</td>
<td>1625 nm</td>
<td>Central wavelength of H-band filter</td>
</tr>
<tr>
<td>F_{\text{lim}, V}</td>
<td>3.31e-10 Jy</td>
<td>Sensitivity limit (V-band)^a</td>
</tr>
<tr>
<td>F_{\text{lim}, J}</td>
<td>9.12e-10 Jy</td>
<td>Sensitivity limit (J-band)^a</td>
</tr>
<tr>
<td>F_{\text{lim}, H}</td>
<td>8.32e-10 Jy</td>
<td>Sensitivity limit (H-band)^a</td>
</tr>
</tbody>
</table>

Science yield for coronagraphs and starshades (see Morgan’s talk tomorrow)
Visible/mid-IR comparison

- Comparison with mid-IR nuller (4x 2-m, Darwin-like with 5 mas IWA):
  
  - Similar results for 200 and 450 K and radii between 0.5 and 1.75 $R_{\text{Earth}}$: 63 (LUVOIR) vs 85 (DARWIN/TPF-I) detections.
  
  - For mid-IR nuller, 50% of observed planets are around M stars.
The observing challenge

Spectroscopic resolution requirements

- \( \text{O}_2 \) @ 0.76 \( \mu \text{m} \): \( R=70 \)
- \( \text{CO}_2 \) @ 1.2 \( \mu \text{m} \): \( R=35 \)
- \( \text{O}_3 \) @ 0.53 \( \mu \text{m} \): \( R=5 \)
- \( \text{O}_3 \) @ 0.31 \( \mu \text{m} \): \( R=16 \)
- \( \text{O}_2 \) @ 1.26 \( \mu \text{m} \): \( R\approx70 \)
- \( \text{CH}_4 \) @ 1.6 \( \mu \text{m} \): \( R\approx10 \)
- \( \text{CH}_4 \) @ 2.2 \( \mu \text{m} \): \( R\approx10 \)
- \( \text{O}_3 \) @ 9.4 \( \mu \text{m} \): \( R\approx20 \)
- \( \text{CH}_4 \) @ 7.4 \( \mu \text{m} \): \( R\approx15 \)
Example observations (mid-IR)

- Simulated observations (R=40, blue points) imposing a S/N of 20 on continuum detection at 10 µm (Léger et al. in prep).

- All spectral features detected in a single visit (besides O₃):
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Imaging HZ planets from the ground

• NEAR project (“Breakthrough watch”) project to detect the thermal emission (10 µm) of HZ exoplanets around α Cen A and α Cen B

• ~100 hours observations expected to begin in 2019

• Use a state-of-the-art Vortex coronagraph to be installed in VLT/VISIR (see Absil’s talk this afternoon)
Imaging HZ planets from the ground

- ELT/METIS (2025+): mid-infrared imaging and spectroscopy (3-13 μm) of disks and exoplanets
- ~20 cool gas giants detected by RV
- ~10 rocky planets (300K - 500K)

Quanz et al. 2014
Other projects (2025+)

• ELT/PCS: optical imaging and spectroscopy (1-1.7 μm) of disks and exoplanets (see M. Kasper talk)

• PSI/TMT: instruments for exoplanets in reflected and thermal light (see Mawet’s talk)
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Current contrast performance

**Visible:**
\(~10^9\): Fomalhaut b but 150x sep (Kalas et al. 2008)

\(~10^5\): β Pic b but 9x sep (Males et al. 2014)

**Infrared:** \(~10^6\)
- H band: 51 Eri b but 13x sep (Macintosh et al. 2015)
- L band: GJ 504 b but 40x sep (Skemer et al. 2016)
How does it compare to the HZ?

Imaged exoplanets
Inner working angle
Inner working angle

2. Angular separation:
- ~10 to 150 mas

D required for > IWA (2λ/D):
- Visible (550nm): 12m
- Infrared (10µm): ~200m
Need a big aperture!
Need a big aperture!

Exoplanet imaging mission science return increases very quickly with aperture:

Efficiency & Yield
- Number of IWA-accessible planets goes as $D^3$ (Stark et al. 2015)
- Exposure time required to reach given SNR goes as $D^{-4}$ for most low-mass planets (zodi+exozodi → background-limited detection)

Characterization
- Access to longer wavelength spectroscopy, $\lambda_{\text{max}} \sim D$
- Light can be sliced in multiple bins: spectral resolution, time domain, polarization
- Better astrometry → better orbits, dynamical masses
- Resolving (time-variable) structures in exozodi

Data quality
- Higher angular resolution → less confusion between multiple planets, exozodi clumps
- More light → better PSF calibration

Diversity
- Larger aperture allows habitable planets to be observed around a wider range of stellar types
How does performance scale with aperture?

- **Efficiency**: 60%
- **IWA**: 2 I/D
- **Contrast**: 1e10

Potential issues:
- Segments diffraction
- WF stability
- Stellar angular size

(see next talk)