The Search for Life around Nearby Stars: from Remote Sensing to Interstellar Travel

Olivier Guyon
University of Arizona
Astrobiology Center, National Institutes for Natural Sciences (NINS)
Subaru Telescope, National Astronomical Observatory of Japan, National Institutes for Natural Sciences (NINS)
JAXA

Sept 29, 2016, University of Arizona
Habitable zone of a star

Every star has a habitable zone.
What makes planets habitable?

The planet must be in the **habitable zone** of its star: not be too close or too far.

**Venus:** too close, too hot

**Mars:** too far, too cold

Venera 13 lander, survived 127mn at 457 C, 89 atm

Image credit: NASA/JPL-Caltech/MSSS
What makes planets habitable?

Size matters: not too big, not too small

Moon: too small
No atmosphere

Earth

Jupiter: too big
 Mostly gas
lots of planets, \( \sim 10\% \) of stars have potentially habitable planets
~300 billion stars in our galaxy
~300 billion stars in our galaxy

~30 billion habitable planets

If 100 explorers were sent to visit each habitable for 10 seconds (only 300 million planets/explorer)...

... it would take 95 yrs to complete the habitable exoplanets tour ... in our galaxy alone
200 billion galaxies in the observable universe
How do astronomers identify exoplanets?

HIGH PRECISION OPTICAL MEASUREMENTS OF STARLIGHT (indirect techniques)

Earth around Sun at ~30 light year

→ Star position moves by 0.3 micro arcsecond (thickness of a human hair at 20,000 miles)

→ Star velocity is modulated by 10cm / sec (changes light frequency by 1 part in 3,000,000,000)

If Earth-like planet passes in front of Sun-like star, star dims by 70 parts per million (12x12 pixel going dark on a HD TV screen 70 miles away)
**Exoplanet transit**

*If the planet passes in front of its star, we see the star dimming slightly.*

Transit of Venus, June 2012
Directly imaging planet is necessary to find life

We need to take spectra of habitable planets

Spectra of Earth (taken by looking at Earthshine) shows evidence for life and plants

Woolf et al.
Spectroscopic characterization of Earth-sized planets with ELTs

Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired [assumes 1e-8 contrast limit, 1 λ/D IWA]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (models tell us it’s possible)

Space-based ultra-high contrast instrument(s) will image and characterize Earth-like planets around Sun-like stars
Habitable Zones within 5 pc (16 ly)

Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)
Accessible from Northern Site (Mauna Kea)
Accessible from Southern Site (Cerro Amazones)

Requires source to transit at >30deg elevation above horizon
Indirect detection techniques → mass

Astrometry

Radial Velocity

The Radial Velocity Method
Habitable Zones within 5 pc (16 ly):
Astrometry and RV Signal Amplitudes for Earth Analogs

Circle diameter is proportional to 1/distance
Circle color indicates stellar temperature (see scale right of figure)

Astrometry and RV amplitudes are given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)

Expected detection limit for space astrometry (NEAT, THEIA, STEP) F, G, K stars

Expected detection limit for near-IR RV surveys (SPIROU, IRD + others) M-type stars
Habitable Zones within 5 pc (16 ly)

Star Temperature

1. Gliese 1245 A
2. Gliese 1245 B
3. Gliese 674
4. Gliese 440 (white dwarf)
5. Gliese 876 (massive planets in near HZ)
6. Gliese 1002
7. Gliese 3618
8. Gliese 412 A
9. Gliese 412 B
10. AD Leonis
11. Gliese 832

Radial Velocity
(1 pc = 3.26 ly)

ELT imaging
(near-IR)

Space astrometry

ELT imaging
(thermal-IR)

Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)
Beta Pictoris

8 Jupiter mass planet

Orbits young massive star in ~20yr

Beta Pictoris

Hubble Space Telescope • ACS/HRC

ESO VLT image
(Lagrange et al.)
HR8799
Four planets, orbital periods on the order of 100yr
Each planet 5 to 7 Jupiter Mass

Keck telescope image (Marois et. al)
Taking images of exoplanets: Why is it hard?
Exciting future opportunities

Next generation of large telescopes on the ground will be able to image habitable planets around nearby low mass red stars
3 projects, ~30m diameter

Space telescopes with coronagraphs will be able to image and study Earth-like planets around sun-like stars
Giant Magellan Telescope
Coronagraphy ... Using optics tricks to remove starlight (without removing planet light)

We need a better coronagraph... and a larger eye (telescope)
Coronagraphy

Key coronagraph requirements:

- IWA near 1 l/D
- High throughput
- $\sim 1e^{-5}$ raw contrast
- Resilient against stellar angular size (ELTs partially resolve stars)
Water waves diffract around obstacles, edges, and so does light

Waves diffracted by coastline and islands

Ideal image of a distant star by a telescope
Diffraction rings around the image core
GMT coronagraph design

PIAACMC architecture:
  - lossless apodization with aspheric mirrors
  - multi-zone focal plane mask

60% throughput
IWA = 1.3 l/D

optimized for 10% wide band and stellar angular size
(largely) lossless apodization
Creates a PSF with weak Airy rings

Focal plane mask: \(-1 < t < 0\)
Induces destructive interference inside downstream pupil

Lyot stop
Blocks starlight

Inverse PIAA (optional)
Recovers Airy PSF over wide field

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)
Focal plane mask

583 zones
SiO2 (transmissive)
+/- 3 um sag

Optimized for 10% band, partially resolved source
PIAACMC focal plane mask manufacturing

Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)

(a) (b) (c)

Tilted walls of 200 nm pixels

\[ h \text{ [nm]} \]

\[ x \text{ [\mu m]} \]
PIAACMC lab performance @ WFIRST (Kern et al. 2016)

Operates at $1e^{-7}$ contrast, 1.3 I/D IWA
Visible light

non-coronagraphic PSF  Remapped pupil  Coronagraphic image
Performance

1e-7 contrast (top: point source)
3e-6 contrast @ 3 I/D for 6% I/D disk (bottom)

IWA = 1.3 I/D
WFC architecture
game-changers

[1] High-efficiency WFS
M stars are not very bright for ExAO → need high efficiency WFS
For low-order modes (TT), seeing-limited (SHWFS) requires \((D/r_0)^2\) times more light than diffraction-limited WFS (Pyramid)
This is a **40,000x gain for 30m telescope** (assuming \(r_0=15\text{cm}\)) → 11.5 mag gain

[2] Low latency WFC (High-speed WFS + predictive control)
System lag is extremely problematic → creates “ghost” slow speckles that last crossing time
Need ~200us latency (10 kHz system, or slower system + lag compensation)
Predictive control is essential

Wavefront chromaticity is a serious concern when working at ~1e-8 contrast
Visible light (≈0.6 – 0.8 um) photon carry most of the WF information, but science is in near-IR

[4] Fast speckle control, enabled by new detector technologies
Addresses non-common path errors
It doesn't take much to create a 1e-8 speckle!

[5] Real-time telemetry → PSF calibration
WFS telemetry tells us where speckles are → significant gain using telemetry into post-processing
WFC: Contrast limits

Assumptions:

I mag = 8  (WFS – 100 targets)
H mag = 6  (Science)

Noiseless detectors
1.3 l/D IWA coronagraph
30% system efficiency
40% bandwidth in both WFS and science
Time lag = 1.5 WFS frames

Mauna Kea “median” atmosphere
30m: SH-based system, 15cm subapertures

Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster) – same speed as 8m telescope
>10kph per WFS required

Detection limit ~1e-3 at IWA, POOR AVERAGING due to crossing time
More sensitive WFS, can run faster (10kHz) with ~10 kph per WFS frame
Limited by atmosphere chromaticity

~((D/CPA)/r0)^2 flux gain: ~10,000x in flux = 10 mag near IWA
Sensitivity now equivalent to I mag = -2 with SHWFS
300Hz speckle control loop (~1kHz frame rate) is optimal

Residual speckle at ~1e-6 contrast and fast → good averaging to detection limit at ~1e-8
Optimal linear predictive control
(model-free, uses Empirical Orthogonal Functions)

... what dumb people do with fast computers

Collect LOTS of data, and then find the multi-dimensional AR filter that best reproduce current measurement as a function of past measurements (best = least square)

Computationally very intensive: need pseudo-inverse of data matrix

Data matrix size: # of time steps (60,000 for 1kHz system, 1mn telemetry) \times # of AR filter coefficient (10,000 for 1000 modes, 10-step prediction)

Current WF (~1000 modes) = Prediction coefficients (10,000,000 coefficients) \times past measurements (10,000 values)

Detection limit ultimately constrained by RAW contrast (photon noise) → predictive control can push performance deeper
Fig. 3.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.
Fig. 4.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.
Optimal linear predictive control – 8m telescope (model-free, uses Empirical Orthogonal Functions)

8m telescope
mag 8 source (R band)
1kHz sampling + 2ms lag
Photon-noise limited sensor
10% efficiency, 20% bandwidth
r0 = 20cm at 0.6um → 21 rad WFE RMS
7 layer turbulence, most power between 6 and 22 m/s

System dominated by time lag (214nm error)
WFS noise small (9nm RMS over first 400 low-order modes)

Optimal control of 400 zonal actuators
1mn training set → controller
(rolling average of 10 last controllers)

Integrator: RMS = 214 nm (gain = 1)
10-step prediction: RMS = 30.5 nm
Benefits & challenges

Lower wavefront error (30nm vs. >200nm)
Raw contrast improvement: ~100x gain

Relaxed speed requirement
contrast corresponds to 10 kHz WFS lag
→ 10x speed gain

Smother PSF halo
slow speckles are GONE

Computation requirements:
SVD of 60000x4000 dense matrix in <1mn
already met on single GTX980M GPU (laptop)
few 1000s modes @ few kHz can be done on
current hardware

1hr detection limit
(PSF subtraction residual)
Differential detection game-changers

[1] High spectral resolution template matching
   100x – 1000x gain (photon-noise permitting)

   10-100x gain ?

[3] Linear Dark field speckles control
   10-100x gain ?
Coherent Speckle Differential Imaging
Bright field speckles in $\frac{1}{2}$ field dark hole
Linear Dark Field Control (LDFC)

Speckle intensity in the DF are a non-linear function of wavefront errors → current wavefront control technique uses several images (each obtained with a different DM shape) and a non-linear reconstruction algorithm (for example, Electric Field Conjugation – EFC)

Speckle intensity in the BF are linearly coupled to wavefront errors → we have developed a new control scheme using BF light to freeze the wavefront and therefore prevent light from appearing inside the DF
**Example system architecture with instrumentation**

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Woofer DM</strong></td>
<td>~2 kHz speed, 120 x 120 actuators, delivers visible diffraction-limited PSF to visible WFS</td>
</tr>
<tr>
<td><strong>Tweeter DM</strong></td>
<td>10 kHz response, 50x50 actuators, provides high contrast</td>
</tr>
<tr>
<td><strong>Low-IWA coronagraph</strong></td>
<td>High efficiency, speed ~kHz, photon-counting detector</td>
</tr>
<tr>
<td><strong>Speckle control afterburner WFS</strong></td>
<td>Speed ~kHz, photon-counting detector</td>
</tr>
<tr>
<td><strong>Visible light low-latency WFS</strong></td>
<td>Diffraction limited sensitivity</td>
</tr>
<tr>
<td><strong>Visible light</strong></td>
<td>Imaging, spectroscopy, polarimetry, coronagraphy</td>
</tr>
<tr>
<td><strong>Near-IR</strong></td>
<td>Imaging, spectroscopy, polarimetry</td>
</tr>
<tr>
<td><strong>Thermal IR Imaging &amp; spectroscopy</strong></td>
<td></td>
</tr>
</tbody>
</table>

**INSTRUMENTATION**

- **Coronagraphic Low-order WFS uses light rejected by coronagraph**
  - Catches aberrations **BEFORE** they hurt contrast
  - Stellar leakage derived from telemetry

**TT, focus?**

**High-res spectroscopy can detect molecular species and separate speckles from planet spectra**
Can we do it?

GPI, SPHERE operate at $\sim 1e^{-6}$ contrast at $>0.3$ arcsec separation, fall short of goal, but current technologies exist to meet requirements.

However, most of what we need has never been tested on sky and integrated into a system → this is what we need to do NOW on current large telescopes.

It takes yrs of hard work to put all of this together, learn what works, and optimize algorithms / designs (including data reduction)

prototypes to ELT systems

**SCExAO program** on Subaru is technology development platform to mature techniques and system for ELTs

**MagAO-X** plays similar role on Magellan. Strong collaboration between the two projects (technology transfer, shared algorithms/software)

**Focused efforts on Palomar & Keck** validate key technologies (Vortex coronagraphy, LOWFS, HR template matching)

**Lab efforts** @ UofA, Caltech, JPL, Princeton, Stanford
Subaru Coronagraphic Extreme Adaptive Optics
SCExAO/Subaru → TMT
CHARIS

Near-IR nuller

HiCIAO or MKIDS

Near-IR InGaAs cameras → to be replaced with EI technology

SAPHIRA

SCExAO near-IR bench, End 2016

SAPHIRA

HiCIAO or MKIDS

Near-IR InGaAs cameras → to be replaced with EI technology

SAPHIRA
Coronagraphs

Deformable mirror
How SCExAO achieves high contrast

(1) Small IWA, high throughput Coronagraphy
→ removes diffraction (Airy rings), transmits r>1 l/D region

(2) Extreme-AO with fast diffraction-limited WFS
→ removes wavefront errors

(3) Near-IR LOWFS
→ keeps star centered on coronagraph and controls Focus, Astig, etc..
→ records residual WF errors to help process data

(4) Fast Near-IR Speckle control
→ modulates, removes and calibrates residual speckles

Requires fast low-noise detectors

Speckle nulling on-sky
Facility Adaptive Optics system

Sharpens image

Extreme-AO LOOP

High speed pyramid wavefront sensor

Measures aberrations

3.7 kHz

CORONAGRAPHIC LOW ORDER LOOP

Near-IR camera

Measures low-order aberrations

10-200 Hz

800 – 2500 nm (rejected by coronagraph)

MKIDs camera

Measures residual starlight

~2 kHz

SPECKLE CONTROL LOOP

CHARIS spectrograph

Exoplanet spectra

Slow speckle calibration

800 – 1350 nm

Near-IR instruments

Nuller, HiCIAO, IRD

~0.5 Hz

Visible light instruments

VAMPIRES, FIRST, RHEA

2000 actuator Deformable mirror

removes starlight

>800nm

<800nm
Low latency WFC in visible light at the diffraction limit sensitivity

2000 actuators MEMs DM running at 3.6 kHz deep depletion EMCCD

Non-modulated pyramid WFS cannot rely on slope computations → full WFS image is multiplied by control matrix

Now delivering 90% SR in H

Recent upgrade allows 3.6kHz loop operation with zonal and modal reconstruction → low-latency control → modal reconstruction for predictive / LQG control (under development)

SCExAO uses 30,000 cores running @1.3GHz
Current PSF stability @ SCExAO

725nm (VAMPIRES camera)
55 Hz sampling (bottom)
co-added (right)

1630nm (SCExAO internal camera)
3 Hz sampling

Current issues:
- residual vibration → dedicated TT loop, accelerometers on telescope
- occasional DM edge "flaring" → filtering in control loop
Preliminary VAMPIRES science

Circumstellar dust around Red Supergiant μ Cephei

Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely $\text{Al}_2\text{O}_3$) important for unexplained extension of RSG atmospheres.

**Inner radius:** $9.3 \pm 0.2$ mas (which is roughly $R_{\text{star}}$)

**Scattered-light fraction:** $0.081 \pm 0.002$

**PA of major axis:** $28 \pm 3.7\,^\circ$ • **Aspect ratio:** $1.24 \pm 0.03$

**Left:** model image, shown in polarized intensity. **Middle:** model image show in four polarisations. **Right:** Model image (intensity), shown with wide field MIR image (from de Wit et al. 2008 – green box shows relative scales. Axis of extension in MIR image aligns with the close-in VAMPIRES image.
Neptune with CHARIS + SCExAO
CHARIS data cube @ SCExAO

Calibration speckle
Modulated at 3.5kHz for decoherencing

\( \lambda = 1.93 \, \mu m \)
Managing chromaticity

Near-IR low-order coronagraphic WFC (Singh et al. 2015)

Closed loop atmospheric dispersion compensation (Pathak et al. 2016)
Systematically removing speckles

Presence of static & slow-varying aberrations in the path of science camera sets contrast limit at present

Typical SCExAO PSF

Spatial frequency in pupil

Matching speckles in the image
speckle nulling results on-sky (June 2014)

Single frames: 50 us

Sum of 5000 frames: shift and add

Meta data:
Date: 2nd or June
Target: RX Boo (also repeated on Vega)
Seeing: <0.6"
AO correction: 0.06" post-AO corrected in H- band (0.04" is diffraction-limit)
Coronagraph: None (used Vortex on Vega)

Martinache. et. al.
SAPHIRA Infrared APD array

HgCdTe avalanche photodiode manufactured by Selex

Specifications
320 x 256 x 24μm
32 outputs
5 MHz/Pix

50 frame average
MKIDS camera (built by UCSB for SCExAO)

Photon-counting, wavelength resolving 100x200 pixel camera

Pixels are microwave resonators at ~100mK photon hits → resonator frequency changes

Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

Delivery to SCExAO in CY2017
Electron-injector nearIR camera
(Northwestern Univ / Keck foundation)

Electron-injector nearIR camera

Electron-injector nearIR camera

1 μm Electron-injection low-order wavefront sensing (pointing) camera

3 μm Electron-injection speckle imaging camera
1 \frac{\lambda}{D} = 1600\text{nm} \\
D = 8\text{m} \\

1 \frac{\lambda}{D} = 1600\text{nm} \\
D = 30\text{m} \\

Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired [ assumes 1e-8 contrast limit, 1 \frac{I}{D \text{ IWA}} ]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to \sim 1e-7 (models tell us it’s possible)
Key technologies are rapidly advancing from paper concepts to system integration.

- High performance coronagraphy
- Diffraction-limited WFS
- Coronagraphic LOWFS
- Multi-lambda WFS
- Atmospheric speckle control
- Optimal predictive control
- Real-time WFS → PSF calibration
- Coherent differential imaging
- High spectral R template matching
- Linear Dark Field Control
Direct imaging with ELTs - Conclusions

Low-hanging fruits (Prox Cen B) can be imaged on ELTs with current technology.

ELTs can probably operate at ~1e-5/1e-6 raw contrast and photon-noise limited detection limit.

→ characterization (spectroscopy) of 1e-8 habitable planets accessible around >100 nearby stars, mainly near-IR/visible.

Aggressive technology validation and system level testing is ongoing, aligned with (near-)first light deployment.
Interstellar travel: pre-2000 studies

Several serious studies (Longshot, Orion, Deadalus)

Propulsion challenge is significant

Project Orion – using nuclear propulsion, massive spacecraft
Starshot project

Leverages current/future technology developments:

- small spacecraft (~gram)
- Ground-based laser propulsion (“don't carry your fuel”)
Starshot project – overview

Goal speed: 20% speed of light. Acceleration phase: few minutes, >10,000 G. Travel time: few decades. Flyby, no deceleration phase.

Launch many nanocrafts ($$ is in launch facility and technology development, not in individual nanocrafts)

**Significant technology challenges**:

- Laser array power and cophasing
- Sail/nanocraft: reflectivity, stability (spinning sail ?), Interstellar medium abrasion, High-G low mass electronics, camera, battery
- Navigation (photon thrusters for course correction)
- Communication during flight (for course correction) and upon arrival (beam back images)

Next steps: Sub-scale demonstration of sail laser propulsion reaching ~100km/s (in vacuum pipe) + concept studies for key challenging aspects of project

Breakthrough Initiatives Foundation will request proposals from industry/university teams to work on the hard problems... RFPs are under preparation – get ready!