Anybody out there?

Optical tricks to look for life around nearby stars

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See also: projectpanoptes.org
Outline

**Introduction**
Why direct imaging? Why is it difficult?

**Technology**
High performance PIAA coronagraphy, recent lab results, coronagraphy + WFC

**Scientific Opportunities**
SPACE: Direct imaging of Earth-like planets around Sun-like stars
GROUND: **Imaging habitable planets around M-type stars with ELTs**; SCExAO as a precursor

**project PANOPTES**
engaging citizen scientists, amateur astronomers and schools in the search for other worlds
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Every star has a habitable zone
Planets identified – we are now starting to identify Earth-like planets
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.
Taking images of exoplanets: Why is it hard?
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Coronagraphy ... Using optics tricks to remove starlight (without removing planet light)

← Olivier's thumb...
the simplest coronagraph
 Doesn't work well enough to see planets around other stars

We need a better coronagraph... and a larger eye (telescope)
What is light: particle or wave?

1807: Thomas Young publishes his double-slit experiment result … cannot be explained by Newton's corpuscular theory of light

1818: French academy of science committee launches a competition to explain nature of light

Augustin-Jean Fresnel submits wave theory of light

Simeon-Denis Poisson finds a flaw in Fresnel's theory: According to Fresnel's equations, a bright spot should appear in the shadow of a circular obstacle → this absurd result disproves Fresnel's theory

Dominique-Francois-Jean Arago, head of the committee, performs the experiment. He finds the predicted spot → Fresnel wins the competition
Water waves diffract around obstacles, edges, and so does light.
Why coronagraphy?

Conventional imaging systems are not suitable for high contrast (even if perfect) due to diffraction.
Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

+ Simple, robust, achromatic
- low efficiency for high contrast

Jacquinot & Roisin-Dossier 1964
Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.

- No loss in angular resolution or sensitivity
- Achromatic (with mirrors)
- Small inner working angle

→ Gain ~x2 to x3 in telescope diameter over previous concepts

Guyon, Belikov, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present
PIAA optics
PIAA testbed at JPL
PIAA testbed at NASA JPL: lab results

Location of the star (mostly blocked)

Contrast ~5e-10 between 2 and 4 I/D

An Earth-like planets could be seen!
PIAA testbed at NASA Ames

This area is more than one million times fainter than the star.
EXCEDE
EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

Dr. Glenn Schneider (PI)
Dr. Olivier Guyon (IS)
Steward Observatory, The University of Arizona
NASA Ames, Lockheed Martin

Mission Overview

Studying the formation, evolution, and architectures of exoplanetary systems, and characterizing circumstellar environments in habitable zones.

- 0.7 meter off-axis visible-light telescope
- Active Starlight Suppression System:
  - PIIA Coronagraph (~1 I/D IWA)
  - 2000-Element MEMS Deformable Mirror
  - Low-Order Wavefront Sensor
- Two-band Imaging Polarimeter
- Three-year mission (2000-km LEO Sun-synchronous orbit)
  - Appx. 350 targets hosting Protoplanetary, Transitional, & Debris Disks, and high-priority EGPs
- Newly NASA-funded 2-year Tech. Dev program
  - Partnership contributions from UofA, Lockheed-Martin, NASA/AMES
The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system
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Exo-Earth targets within 20 pc
Exo-Earth targets within 20 pc

ELTs in near-IR

2 to 4m space telescope in visible light
2.4-m ex-NRO Telescope, Two instruments
Custom coating on PM

Primary mirror coated with micro-dots covering ~1% of surface area, used for astrometric calibration

EXACT's high contrast imaging camera extracts a narrow field of view in the center of the astrometric camera's intermediate focus

EXACT's optical design WF error over 15'x15' field [unit = \(\mu m\)]

EXACT's astrometric wide field camera design offers <60 nm WF error over a 15'x15' field
EXACT can identify and characterize Earth-mass habitable planets around ~20 stars.
Habitable Planets Spectroscopy in near-IR

Atmosphere transmission:
- $\text{O}_2$ (see Kawara et al. 2012)
- $\text{H}_2\text{O}$
- $\text{CO}_2$
- $\text{CH}_4$

Polarimetry
- Cloud cover, variability
- Rotation period

Reflectivity from ground in atmosphere transparency bands
- (Ice cap, desert, ocean etc...)

Credit: NASA/Ames Airborne Tracking Sunphotometer (AATS)
Reflected light planets

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance
(assumes Earth albedo, contrast and separation for max elongation)
Reflected light planets

First cut limits meant to exclude clearly impossible targets
→ used to identify potential targets → instrument requirements

<table>
<thead>
<tr>
<th>Limit/constraints</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular Separation</td>
<td>Limit imposed by coronagraph (see section 4). Corresponds to 11mas on a 30-m telescope in H band.</td>
</tr>
<tr>
<td>Contrast</td>
<td>High contrast imaging limit (see section 5)</td>
</tr>
<tr>
<td>Star brightness</td>
<td>Required for high efficiency wavefront correction (see section 5)</td>
</tr>
<tr>
<td>Planet Brightness</td>
<td>Faint detection limit</td>
</tr>
</tbody>
</table>

background-limited SNR > 10 in H band image in 1 hr on 30-m telescope (assuming 15% efficiency)
Reflected light planets

274 targets survive the first cut
Strong correlation between planet apparent brightness and system distance
Reflected light planets

Most targets are red stars (M type), around $V \sim 10$, $R \sim 9$
2 white dwarfs: 40 Eri B and Sirius B
Early type stars → contrast too challenging
### Reflected light planets

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance (assumes Earth albedo, contrast and separation for max elongation)

#### MOST FAVORABLE TARGETS

<table>
<thead>
<tr>
<th>STAR</th>
<th>PLANET</th>
<th>Notes, Multiplicity</th>
</tr>
</thead>
</table>
| Proxima Centauri (GL511) | M5.5 | 1.30 pc | 0.138 $R_{\text{Sun}}$ | 8.64e-04 | 11.00 | 9.56 | 4.83 | 22.69 mas | 8.05e-07 | 20.07 | RV measurement exclude planet above 3 Earth mass in HZ [Endl & Kurster 2008]
| Barnard's Star (GL699) | M4 | 1.83 pc | 0.193 $R_{\text{Sun}}$ | 4.96e-03 | 9.50 | 8.18 | 4.83 | 38.41 mas | 1.40e-07 | 21.97 |
| Kruger 60 B (GL860B) | M4 | 3.97 pc | 0.2 $R_{\text{Sun}}$ | 5.81e-03 | 11.30 | 9.90 | 5.04 | 19.20 mas | 1.20e-07 | 22.35 |
| Ross 154 (GI729) | M4.5 | 2.93 pc | 0.2 $R_{\text{Sun}}$ | 5.09e-03 | 10.40 | 9.11 | 5.66 | 24.34 mas | 1.37e-07 | 22.82 |
| Ross 128 (GI447) | M4.5 | 3.32 pc | 0.2 $R_{\text{Sun}}$ | 3.98e-03 | 11.10 | 9.77 | 5.95 | 18.99 mas | 1.75e-07 | 22.84 |
| Ross 614 A (GL234A) | M4.5 | 4.13 pc | 0.2 $R_{\text{Sun}}$ | 5.23e-03 | 11.10 | 9.82 | 5.75 | 17.51 mas | 1.33e-07 | 22.95 | Double star (sep=3.8 AU) |
| Gl682 | M3.5 | 4.73 pc | 0.26 $R_{\text{Sun}}$ | 6.41e-03 | 10.90 | 9.70 | 5.92 | 16.93 mas | 1.09e-07 | 23.33 |
| Groombridge 34 B (GI15B) | M6 | 3.45 pc | 0.18 $R_{\text{Sun}}$ | 5.25e-03 | 11.00 | 9.61 | 6.19 | 20.98 mas | 1.33e-07 | 23.39 | 150 AU from M2 primary |
| 40 Eri C (GI166C) | M4.5 | 4.83 pc | 0.23 $R_{\text{Sun}}$ | 5.92e-03 | 11.10 | 9.88 | 6.28 | 15.93 mas | 1.18e-07 | 23.61 | 35AU from 40 Eri B (white dwarf), 420 AU from 40 Eri A (K1) |
| GJ 3379 | M4 | 5.37 pc | 0.24 $R_{\text{Sun}}$ | 6.56e-03 | 11.30 | 10.06 | 6.31 | 15.09 mas | 1.06e-07 | 23.75 |

[1] Angular diameter (uniform disk, non limb-darkened value) measured by optical interferometry with VLTI [Demory et al. 2009](#)  
[2] Uniform disk angular diameter from Lane et al. 2001  
[3] No direct measurement. Approximate radius is given. If possible, radius is extrapolated from photometry using K magnitude and radius vs. absolute K magnitude relationship in [Demory et al. 2009](#)

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**Requirement:** ~1e-7 contrast, ~15mas, mR ~ 9.5 guide star
Proxima Centauri
Reflected light planets

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance
(assumes Earth albedo, contrast and separation for max elongation)
Photon-noise limited SNR limit in H band

*Earth like planet around M type star at 5pc*

Assumptions:

- D = 30m telescope, $m_H=14.4$ arcsec$^{-2}$ background, 20mas aperture
- 15% efficiency (coatings, detector), 0.3 um bandpass (H band), 1 hr exposure
- planet $m_H = 25.2$ (Earth at 5pc)
- background = 230 ph/sec
- Planet = 27.5 ph/sec
- Star = 9.98e8 ph/sec ($m_H=6.3$, M4 stellar type)
- Star / Planet contrast = 3.6e7

Detection SNR

- H band ($R\sim5$)
  - Imaging, no starlight: 102 [356]
  - Imaging, 1e5 raw contrast: 16.31 [65]
  - Imaging, 1e4 raw contrast: 5.16 [20.6]
  - Aperture masking, 100% efficiency: 0.05 [0.2]

Spectroscopy SNR

- $R = 100$
  - Imaging, no starlight: 23.5 [83]
  - Imaging, 1e5 raw contrast: 3.8 [15]
  - Imaging, 1e4 raw contrast: 1.2 [4.8]
  - Aperture masking, 100% efficiency: hopeless...

SuperEarth at 5pc around M star (4x Earth flux, 2x diameter)
Requirements, Top challenges

Efficient coronagraphy
... down to 1 l/D separation on segmented pupils
  Coronagraph design
  Chromaticity
  Stellar angular size

Wavefront control
(getting raw contrast at or below 1e-4 at 1 l/D)
  Efficient sensing of low order aberrations
  Control and calibration of pointing errors

Wavefront calibration to 1e-7
(separating scattered light from planet light)
  Main issues: time lag, chromatic effects, systematics
  The need for nearIR wavefront modulation and correction
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit.

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

Lossless apodization with remapping optics (PIAA)
Conventional apodizer (optional)
Phase-shifting partially transmissive circular focal plane mask
Lyot mask (exact pupil geometry)
Inverse PIAA module

Light intensity

Pie A
|Ψ_A|

|Ψ_B|

|Ψ_C|

Lmask
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit

Pupil shape does not matter !!!
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit.
Coronagraphy: Stellar angular size

On ELT in near-IR, nearby M dwarf is about 0.1 to 0.5 mas radius = 0.01 to 0.05 l/D

→ for 1 l/D IWA coronagraph
RAW contrast limited to ~1e5
Wavefront control

Can we reach 1e-4 RAW contrast in the 1 to 2 l/D range?

Goal: ~1e-5 contrast at 1 l/D

We are not that far from it with current technology...

Conventional high order ExAO on 8-m class telescope achieves ~1e-3 contrast in near-IR at few l/D

Moving to 3x larger telescope diameter will help (dilute speckle halo) – at equal SR, 10x gain in contrast → 1e-4

BUT we can EASILY do much better by:

1. Using diffraction-limited WFS (Pyramid with little or no modulation, nICWFS, Zernike etc...)
   For Tip-tilt, gain in flux is \((D/r_0)^2 = 90,000\) on 30m telescope (12.8 mag)

2. Making use of predictive control in the control loop (inner PSF flux dominated by time lag)
Wavefront calibration to $\sim 1\times10^7$ contrast

SDI, ADI WILL NOT WORK AT 1 I/D !!!

Focal plane speckle modulation appears to be very promising:
- no need for high optical quality
- non-common path errors
- detectors now exist to do this efficiently

→ SCExAO (and others...) using this technique

Works well in the lab when things are stable... will it also work on sky with speckles moving around?
Focal plane AO and speckle calibration

Use Deformable Mirror (DM) to add speckles

**SENSING**: Put “test speckles” to measure speckles in the image, watch how they interfere

**CORRECTION**: Put “anti speckles” on top of “speckles” to have destructive interference between the two (Electric Field Conjugation, Give’on et al 2007)

**CALIBRATION**: If there is a real planet (and not a speckle) it will not interfere with the test speckles

Fundamental advantage: Uses science detector for wavefront sensing: “What you see is EXACTLY what needs to be removed / calibrated”
Speckle nulling control software
(Martinache et. al)

Readout overhead with HiCIAO ~ 10-15 seconds prevents from using it in an even remotely efficient close-loop.

Speckle nulling relies on the analysis of images acquired with the internal “science” camera. Readout is faster than necessary (~50 Hz), however integration time is limited by the dark current to ~20 milli-seconds.

The software can track an arbitrary number of diffraction features, and iteratively drives them down with the DM by adding speckles that interfere destructively with the diffraction (in half the field of view).

After several iterations of speckle nulling, long exposures with HiCIAO can be used for science purposes, benefiting from a cleaner image at small angular separation.
Active speckle control (Martinache et al.)

Active MEMS DM to replace a passive ADI approach at small angular separation

Taking advantage of the full PIAA - focal plane mask - PIAA^{-1} optical configuration

SCExAO’s PIAA coronagraph permits speckle control from 1.5 to 14 \lambda/D
Raw contrast \sim 3e^{-4} inside the DM control region

Martinache et al. 2012, PASP, 124, 1288
Improved sensitivity (Martinache et. al)

Detection limits are fundamentally set by the local effect of temporal fluctuations in the diffraction. The proper metric to estimate the benefit of the technique: standard deviation across the same data-cubes for the “flat” and the “optimized” DM volt-maps.

Two observations:
- overall, the standard of the image after speckle nulling is reduced over the entire frame ($\times \sim 1/2$)
- inside the control region, the sensitivity gain tops at a factor of $\sim 7$.

At the smallest angular separations (how many $I/D$?), the detection limit is improved by 1-2 magnitudes.

Martinache et al, 2013, in preparation
Imaging habitable planets with ELTs

Habitable planets can be imaged with ELTs around low-mass stars. Spectroscopy of several targets could also be done at a very useful $R \sim 100 \rightarrow$ this is the easiest quickest way to characterize habitable planets.

This requires aggressive IWA system able to work at 1 lambda/D and somewhat unusual (but not particularly challenging) technical choices.

Technologies are being matured now, and should be ready in 10yrs ASSUMING WE WORK ON IT.

This should be a focused experiment for <100 targets. Can be deployed quickly and cheap $\rightarrow$ great science per $\$ !!!!

SCExAO is a precursor to such a system. A SCExAO-like system could be placed on an ELT in a short time, as optical interfaces for narrow FOV system are relatively easy.
Detecting planets from space and ground

------------- Space -------------

Habitable planets can be imaged around nearby Sun-like stars with 2-4m telescope

------------- Ground -------------

SCExAO on Subaru will image giant planets in the habitable zone of nearby stars

Next generation of 30-m telescopes will image habitable planets around nearby low-mass stars
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Exoplanet transit: An easier way to detect a planet
If the planet passes in front of its star, we see the star dimming slightly

Transit of Venus, June 2012
How citizen scientists, schools, amateur astronomers can help discover exoplanets using digital cameras

Project PANOPTES

Panoptic Astronomical Networked Optical observatory for Transiting Exoplanets Survey

Check: projectpanoptes.org
Email: users@projectpanoptes.org
PANOPTES goals

Discovering transiting exoplanets requires monitoring large parts of the sky for long periods of time.

Amateur astronomers, citizen scientists are very good at this, and schools can participate with student team projects.

BUT:
- Cost must be small to get strong community participation
- Technical challenges: hardware, software
- Requires coordination (data must be combined between many observers)

→ project PANOpTES is aimed at solving these 3 problems to enable a world-wide network of low-cost imaging units for exoplanet transit discoveries
→ PANOpTES is aimed at enabling collaboration between citizen scientists, amateur astronomers, schools and “real” astronomers.
Enabling technologies

Digital cameras are relatively cheap and high quality

- ~20 Mpix
- $\leq 3e^{-}$ readout noise
- Outstanding cosmetic quality
- Fast readout ($<<1$sec)
- Robust construction
- Low dark current ($<<$ sky background)

... for a few $100s$

Using many digital cameras + lenses is the most cost-effective way to cover large parts of the sky with good sensitivity (Few $1000s$ per square degree square meter of etendue)
Phase 1 (completed)

GOALS:

Demonstrate low-cost reliable hardware solution
  → prototype system has been running for 2 yrs

Demonstrate that high precision photometry can be achieved with low-cost digital cameras
  *Color camera have complex pixel / star interaction*
    → demonstrated % level photometry in 1mn exposure with a single camera
    → demonstrated that a single camera can detect a single transit
PANOPTES prototype unit at Mauna Loa observatory
Example image (Cygnus field):
>100,000 stars in a single image
Example image – 315 sec exposure, ISO 100 (March 1, 2011)
Test on star HD54743 ($V=9.35$)
1 mn cadence
Test on star HD54743 (V=9.35) 1 mn cadence
Test on star HD54743 (V=9.35) 1 mn cadence

<table>
<thead>
<tr>
<th>Error term</th>
<th>R channel</th>
<th>G channel</th>
<th>B channel</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric Scintillation</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td>Photon Noise</td>
<td>2.79%</td>
<td>1.00%</td>
<td>2.24%</td>
<td>mV=9.35, includes background contribution (bright time, r=40arcsec mask)</td>
</tr>
<tr>
<td>Readout Noise</td>
<td>0.40%</td>
<td>0.23%</td>
<td>0.71%</td>
<td></td>
</tr>
<tr>
<td>Flat field error</td>
<td>0.5%</td>
<td>0.4%</td>
<td>0.5%</td>
<td>Error term irrelevant with good tracking</td>
</tr>
<tr>
<td>Total (expected)</td>
<td>2.88%</td>
<td>1.14%</td>
<td>2.42%</td>
<td></td>
</tr>
<tr>
<td>Achieved</td>
<td>2.48%</td>
<td>2.04%</td>
<td>3.51%</td>
<td></td>
</tr>
</tbody>
</table>
Next steps

Build more units, deploy them around the globe for 24hr coverage
Partner with schools, amateur astronomers, and existing exoplanet transit surveys

Set up data storage and processing hub