Anybody out there?

Optical Tricks to Find and Study Exoplanets

Contact: oliv.guyon@gmail.com
ALL known Planets from 1846 to 1989
Planets identified – we are now starting to identify Earth-size planets
Oddballs

**PSR 1257+12** : 3 planets around a pulsar

How could planets survive a supernova? Planets may have formed from debris after the supernova explosion.

**51 Peg b** : The first confirmed “Hot Jupiter”

A Jupiter-size planet at only 5.3% of the Sun-Earth distance from its host star, orbiting in 4.2 days.
Exoplanet Detection Methods Visualized

Simple Telescope
A twinkling star caused by atmospheric effects

Pulsar Timing
Pulsar Frequency by Radio [orbit • mass]
[5]

Radial Velocity
Star Motion by Doppler Effect [orbit • mass]
[511]

Transit
Star Brightness by Eclipse [orbit • radius • atmosphere]
[1,137]

Astrometry
Star Motion by Imaging [orbit • mass]
[1]

Microlensing
Star Brightness by Lensing [orbit • mass]
[26]

Direct Imaging
Planet Brightness by Imaging [orbit • radius • atmosphere]
[35]

Stars appear to twinkle with many colors as observed by the naked eye or simple telescopes.

Precise instruments were required to remove this atmospheric effect and reveal planets.

Since 1992 we know of over 1,800 planets around other stars detected by six main methods.

Planet effects on stars are exaggerated for clarity. Numbers correspond to the number of planets detected so far by each method.
Exoplanet transit

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

Transit of Venus, June 2012
>10% of stars have potentially habitable planet
First potentially habitable planets now identified
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
Beta Pictoris

8 Jupiter mass planet

Orbits young massive star in ~20yr

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?
Coronagraphy … Using optics tricks to remove starlight (without removing planet light)

← Olivier's thumb...
the easiest 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.

Waves diffracted by coastline and islands

Ideal image of a distant star by a telescope
Diffraction rings around the image core
Why coronagraphy?

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

Earth in the visible, d=10pc, 2m telescope

Airy diffraction pattern, linear scale
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
• PIAACMC gets to < 1 I/D with full efficiency, and no contrast limit

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)
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
We use strangely shaped optics to reshape light.
Technology: components

PIAACMC optimized focal plane mask
F/20 beam, 10% bandwidth around 0.5 μm
SiO2, 20 zones, 4 μm max deviation
Vacuum testbeds at JPL
PIAA testbed at NASA JPL: lab results
(B. Kern, O. Guyon, A. Kuhnert et al.)

An Earth-like planets could be seen!

Monochromatic light (800nm, vacuum)

Location of the star (mostly blocked)

$6 \lambda/D_{\text{sky}}$

$\log_{10} I$

3 runs, contrast values averaged from 2 to 4 $\lambda/D$ between $5.10^{-10}$ to $9.10^{-10}$

(figure shows $7.3.10^{-10}$ result)

7.5% wide band (770 – 830 nm, in air)

$5.10^{-8}$ contrast from 2 to 4 $\lambda/D$,
$2.10^{-8}$ contrast from 3 to 4 $\lambda/D$

Contrast performance limited by wavefront instability (test in air)
Testbed at NASA Ames
The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system
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
Detecting planets from space and ground

Exo-Earth targets within 20 pc

ELTs in near-IR

2 to 4m space telescope in visible light
Habitable Planets Spectroscopy in near-IR

Atmosphere transmission:
- O2 (see Kawara et al. 2012)
- H2O
- CO2
- CH4

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)
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: info@projectpanoptes.org
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.

We are developing an easy to assemble, low cost system based on digital SLR cameras to do exoplanet transit survey work.

projectpanoptes.org
info@projectpanoptes.org
Example image (Cygnus field):
>100,000 stars in a single image