Beyond Kepler: Direct Imaging of Earth-like Planets

- Exoplanets: past and present
- How we can image another Earth (work at NASA Ames)
- Future

Rus Belikov

NASA Ames Research Center

MIT EAPS Department Lecture Series, April 25, 2012
Is there another Earth out there?
Is there life on it?
Thousands of years ago, Greek philosophers speculated.

“There are infinite worlds both like and unlike this world of ours...We must believe that in all worlds there are living creatures and planets and other things we see in this world.”

Epicuruis

c. 300 B.C
Some gave their lives...

"There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. The countless worlds in the universe are no worse and no less inhabited than our Earth"

Giordano Bruno
in De L'infinito
Universo E Mondi, 1584
In 1995, a breakthrough: the first planet around another star.

A Swiss team discovers a planet – 51 Pegasi – 48 light years from Earth.
And then the discoveries started rolling in:

“New Planet Seen Outside Solar System”
New York Times
April 19, 1996

“10 More Planets Discovered”
Washington Post
August 6, 2000

“First new solar system discovered”
USA TODAY
April 16, 1999

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CNN.com/SPACE

Exoplanet toll hits 100 as another Jupiter found

June 20, 2002 Posted: 10:07 AM EDT (1407 GMT)

By Richard Stanger
CNN

(CNN) -- Astronomers said this week they had identified at least eight more planets outside our solar system, bringing the number of known or suspected exoplanets to about 100.

The group, unveiled during an unprecedented string of planet discoveries, includes one much like Jupiter, the second such rare find announced within days.
531 planets found so far, around 445 stars
Kepler: 1235 planet candidates, around 997 stars

Wobble method #1: Radial Velocity

Doppler Shift due to Stellar Wobble

Transit Method

(Wobble method #2: Astrometry)

Gravitational Microlensing

Light from a distant star is bent and focused by gravity as a planet passes between the star and Earth.
The Wobble Method
(Radial velocity / astrometry)

Credit: Amir Give'on and Daphna Wegner
The Wobble Method
(Radial velocity)
453 planets found so far, around 385 stars by indirect detection methods

Wobble method #1: Radial Velocity

(Wobble method #2: Astrometry)

Transit Method

Gravitational Microlensing

Light from a distant star is bent and focused by gravity as a planet passes between the star and Earth.
The Transit Method

Credit: Amir Give'on and Daphna Wegner
You can see transits within our Solar System!

Next Venus transit: 2012 June 5-6
Next one after that: 2117 December 10–11

Courtesy Bob Vanderbei
First true exo-Earth detection might come from a NASA mission called Kepler

http://kepler.nasa.gov/
Most planets discovered so far are closer in mass to Jupiter.

This is (mostly) what we’ve found

This is what we are looking for

![Diagram showing planets and a graph related to exoplanet discoveries.](image-url)
First undeniably rocky planet: Kepler 10b

- 4.6 +/- 1.2 Earth masses
- 1.4 Earth radius
  - Hence, density is 8.8 g/cm³
- G-type star
- Distance from the star: 0.01684au
- Period: 0.8
- Temperature: 1833K

- Announcement: Batalha et. al, January 10, 2011
Many of the new planets get too hot or too cold to support life.

Too hot!  Just right!  Too cold!

Most of them have highly elliptical orbits, or are too close to their parent stars.
Gliese 581 d: confirmed potentially habitable planet

- 7-14 Earth masses: Super Earth
- Distance from the star: 0.22au
- Orbital period: 66.8 days
- Receives 30% the intensity of sunlight on Earth (75% of Mars)

- Announced: 21 April 2009
  - Radial velocity
  - Michel Mayor et. al.,
  - Observatory of Geneva
  - HARPS instrument on ESO 3.6m telescope, La Silla, Chille
Kepler exoplanet candidates

http://vimeo.com/19642643

(Courtesy of Jer Thorpe, New York Times' Data Artist in Residence and a visiting professor at New York University)
Holy grail of detection methods: direct imaging

**2M 1207 (2005)**
- Left: VLT, IR light with adaptive optics, April 2004. Gaei Chauvin et al., ESO.
- Brown dwarf host, 8 million years, 1000°C, 5 Jupiter masses, 54 a.u., 2,500 year period.

**GQ Lupi (2005)**
- VLT, NACO adaptive optics infrared camera, March 2005. Ralph Neuhausser et al., ESO.

**1RXS J160929.1-210524 (2008)**
- Solar-type host, 8 million years, 330 a.u., 1800K, 7-11 Jupiter masses.

**HR8799 (2008)**
- 60 million years, 24, 38, 68 a.u.; 10, 10, 7 Jupiter masses.

**Fomalhaut (2008)**
- 200 million years, 0.054-3 Jupiter masses, 115 a.u. 1500K

**Beta Pictoris (2008)**
- VLT, Anne-Marie Lagrange et al., Nov 2008.
- 12 million years, 8 Jupiter masses, 8 a.u. 1500K
Solar system vs. Fomalhaut
What does the Solar System look like from far away?

Credit: Cassini mission
What does the Solar System look like from far away?

- Feb 14, 1990
- 6 light-hours (4 billion miles away)
- Nearest star (Alpha Cen) is 4.2 light YEARS away (2.5 trillion miles away)
- Earth is $\sim 10^{10}$ times (25 magnitudes) dimmer than the Sun, and would appear $\sim 0.8''$ away for Alpha Cen

Credit: Voyager mission
Stars are a billion times brighter...
...than the planet

...hidden in the glare.
Like this firefly.
How we may image another Earth
Main Engineering Challenge

- Contrast: $10^{10}$
- Inner working angle: $\sim 100$ mas
  - ($2 \lambda/D$, or diffraction ring widths)
What are the main obstacles?

Can the Hubble do it?
All waves generate ripples when disturbed by a hard edge: diffraction
Many different solutions (coronagraphs)
My favorite solution to diffraction: 
Soften the edges!
## Shaped Pupil Zoo

(Softening the edges by blocking light)

<table>
<thead>
<tr>
<th>Mask</th>
<th>Star image</th>
<th>S-K Mask</th>
<th>Star image</th>
<th>S-K Mask</th>
<th>Star image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring</td>
<td>Barcode</td>
<td>Cross-barcode</td>
<td>Spiderweb</td>
<td>Starshape</td>
<td></td>
</tr>
</tbody>
</table>

Early ripple designs

ripple1  ripple2  ripple3

Spergel, Kasdin, Vanderbei, Belikov 2003-2007
PIAA: phase-induced amplitude apodization
(Softening the edges by reshaping light)

No photons are wasted!
(well, almost)

- PIAA was invented by Olivier Guyon (originally from France)
- while working at Subaru telescope (Japanese)
- And is being developed by NASA (US agency)

Ruslan Belikov, NASA Ames Coronagraph Laboratory
PIAA Technology Development

Ames Coronagraph Experiment (ACE)

In a partnership with JPL’s HCIT

Ames Coronagraph Testbed
- Dedicated to testing PIAA and related technologies
- In temperature-stabilized air
- Flexible, rapidly reconfigurable
- Initial validation (TRL 1-4) of PIAA and related technologies
  - MEMS DMs
  - WFC architecture trades
  - Alternative masks/occulters
  - PIAAgen2 mirror manufacture

JPL/HCIT
- TRL 4+ validation (including vacuum)
- Testing a variety of coronagraphs

Ruslan Belikov, NASA Ames Coronagraph Laboratory
NASA Ames Coronagraph Experiment (ACE)

- PIAA optics made by Axsys, diamond-turned CF2, 16mm active diameter

![Diagram of PIAA optics and related components]

- Light source (single mode fiber-coupled laser) 650nm
- Collimating lens
- PIAA System
- Focusing lens
- DM (deformable mirror)
- Focal plane occulter
- Lens
- CCD

Ruslan Belikov, NASA Ames Coronagraph Laboratory
Initial Images from the Lab
Main practical problem: optical aberrations
Solution: use a deformable mirror

- Made by Boston Micromachines, 32x32 actuators, 10mm active area

Light source
(single mode fiber-coupled laser)
650nm

Collimating lens  PIAA System  Focusing lens

DM (deformable mirror)

Focal plane occulter

CCD

Lens

Ruslan Belikov, NASA Ames Coronagraph Laboratory
Active thermal control system
Active thermal control ON ↔ Active thermal control OFF

- Outside the enclosure, temperature varies by ~ 0.5K.
- Inside the enclosure (active thermal control OFF), temperatures vary by ~ 50mK, causing tip/tilt errors of about 0.1 λ/D
- With ATC ON, can sustain the following root mean square values:
  - Air T: 0.9mK
  - Table: 0.4mK
  - Water: 1.3mK
  - Tip/tilt: 4.8e-3 λ/D (limited by insufficient tuning of the ATC algorithm)
- According to simulations, such tip/tilt will limit contrast to ~1e-9 at 2 λ/D
Lab results

Ames (PIAA Coronagraph, 2010)
- Contrast: $5.4 \times 10^{-8}$
- IWA: $2 \lambda/D$
- Bandwidth: 650nm monochromatic

JPL’s HCIT (shaped pupils, 2007)
- Contrast: $2.4 \times 10^{-9}$
- IWA: $4 \lambda/D$
- Bandwidth: 10% @ 800nm
Contrast map

Ames testbed current temperature stability
Current BMC DM electronics resolution
Refractive/monochromatic limit

Current contrast with IWA of 2 λ/D
Instabilities (due to ghosts and unstable laser)

Approximate limit with no enclosure
Polarization issues (birefringence, etc.)
Occulter edge effects (no Lyot stop)

CCD artifacts (when at first focus with no occulter)
No wavefront control, 2 λ/D
No coronagraph

Current contrast with IWA of 4 λ/D
The L3-Tinsley NIBF (Narrow Ion Beam Figuring) system

PIAA Mirrors

PIAA M2 error map

- Mirrors are critical for broadband operation
- Will be tested at JPL and Ames
- PIAA M2 has been completed, with rms surface figure of 3.8nm (out to 90 cycles per aperture)
- PIAA M1 currently being processed
- Simulations show that with a 2DM wavefront control system, this surface figure will enable (in absence of other limiting factors) $\sim 4e^{-10}$ contrast at 2 $\lambda/D$ in a 760-840nm band.

Ruslan Belikov, NASA Ames Coronagraph Laboratory
ACE team members and collaborators

**NASA Ames Research Center**
- Tom Greene: ARC testbed director
- Peter Zell: ARC testbed manager
- Rus Belikov: technical lead
- Eugene Puuzhnik: experiments
- Fred Witteborn: thermal enclosure
- Dana Lynch: optical design

**NASA Jet Propulsion Lab**
- John Trauger
- Andy Kuhnert
- Brian Kern
- Marie Levine
- Wesley Traub
- Stuart Shaklan
- Amir Give'on
- Laurent Pueyo

**Tinsley Laboratories**
(*PIAA mirror manufacture*)
- Daniel Jay
- Asfaw Bekele
- Lee Dettmann
- Bridget Peters
- Titus Roff
- Clay Sylvester

**UofA/Subaru**
(*PIAA design and consulting*)
- Olivier Guyon

**UCSC**
(*DM characterization*)
- Donald Gavel
- Daren Dillon

**Lockheed Martin**
(*Optical design*)
- Rick Kendrick
- Rob Sigler
- Alice Palmer
Future
A Sampling of Possible Missions
(using PIAA)

Simulated exoEarth images in
the 500-600nm band
(with 1 zodi and exozodi)

PECO mission concept
(Guyon et. al.,)

Alpha Centauri

Courtesty of K. Cahoy

Tau Ceti

ACCESS (1.5m)
(Trauger et. al., Vallone et. al.)

EXCEDE (0.7m)
(Schneider et. al.)

WFCT (4m)
(Angel et. al.)

Planetscope (0.5m)
(Traub et. al.)
The New Worlds Observer features a distant external occulter between a telescope and a nearby star. The occulter removes the direct light from the star, revealing the planetary system free from stellar glare.

DAVINCI has the potential to detect many exoplanets, including exo-Earths, using four 1-meter telescopes arrayed on a 4-meter baseline.

The Extrasolar Planetary Imaging Coronagraph (EPIC) is a medium-class mission to study exoplanets. The mission science goals are to detect and characterize gas giant planets, and to study exoplanetary system architectures. A system-level demonstration of 10^6 contrast white light nulling is currently underway at Goddard Space Flight Center.
Once we have an image of an exo-Earth what can we do with it?

Simulation of a PECO image of an exo-Earth around Alpha Centauri
Photometry
(can determine length of day, surface type, weather)

Spectroscopy (composition)

Water
Oxygen
Atmospheric Pressure (Rayleigh Scattering)
Plant Life: Red Edge!

Red Edge

Seager et al. 2005; Data from Middleton & Sullivan 2000
"You can't imagine how tight our budget is. We can only work with single-digit numbers."

By Sydney Harris
The 2010 Astrophysics Decadal survey (Astro2010)

- Negotiated by NRC with Agencies (NASA, NSF, DOE)
  - The Committee on Astro2010 will survey the field of space- and ground-based astronomy and astrophysics, recommending priorities for the most important scientific and technical activities of the decade 2010-2020. The principal goals of the study will be to carry out an assessment of activities in astronomy and astrophysics, including both new and previously identified concepts, and to prepare a concise report that will be addressed to the agencies supporting the field, the Congressional committees with jurisdiction over those agencies, the scientific community, and the public.

- RECOMMENDED PROGRAM:
  - Large-scale (prioritized)
    1. Wide Field InfraRed Survey Telescope (WFIRST)
    2. Explorer Program augmentation
    3. Laser Interferometer Space Antenna (LISA)
    4. International X-ray Observatory (IXO)
  - Mid-scale (prioritized)
    1. New Worlds Technology Development Program
    2. Inflation Technology Development Program
  - Small-scale
Mission to resolve features on planets: 2050?

Simulated Planet Imager View of the Earth

Probe to Alpha Centauri: “before this century is out” – Geoff Marcy
How will we go to an exo-Earth?

1 Million travelers, 100 Million ton mass, ~ $ 20 Trillion, Launch 2500 A.D.

600 km/s cruising speed (lower power, softer collisions)

One-way voyage: 10,000 years to \( \varepsilon \) Eridani

10 decks: water shielding in outermost deck

living/working floor area: 125 m\(^2\)/person

On-board observatories

2 km

Great Pyramid of Cheops, to scale, for comparison; has 1/16 mass of ship

1 rpm yields 1 g of inward acceleration
Possible implications of finding another “pale blue dot”?

- Realizing we may not be alone
- Save the human race
- Legacy of our generation
- Inspiration, and learning about ourselves
"We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And to know the place for the first time.
Through the unknown, remembered gate
When the last of Earth left to discover
Is that which was the beginning..."

T. S. Eliot (1942)
from 'Four Quartets'

More information about NASA's exoplanet program:
http://planetquest.jpl.nasa.gov/

More information about the PECO mission and ACE lab:
http://caao.as.arizona.edu/PECO/
backup
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Science Objectives

- Building on the science priorities identified by the survey, the recommended program is organized by three science objectives that represent its scope:
  - Cosmic Dawn
  - New Worlds
  - Physics of the Universe

- Success in attaining these science goals will enable progress on a much broader front
- Also foster unanticipated discoveries
Recommended Program

- Large-scale (prioritized)
  1. Wide Field InfraRed Survey Telescope (WFIRST)
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- Mid-scale (prioritized)
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- Small-scale
WFIRST - Science

Near infrared wide-field telescope with a set of key science objectives:

- **Dark energy** (part of a coherent ground-space strategy):
  - Baryon acoustic oscillations
  - Distant supernovae
  - Weak lensing

- **Exoplanet statistics**
  - Gravitational microlensing

- Guest investigator mode enabling survey investigations
To achieve New Worlds objective – studying nearby, habitable exoplanets - need preliminary observations before choosing a flagship mission:

- Planetary demography over wide range of conditions:
  - Kepler, WFIRST, integrated ground-based program

- Measurement of zodiacal light:
  - Ground-based telescopes.
  - Sub-orbital and explorer mission opportunities.

In parallel, need technology development for competing approaches to make informed choice in second half of decade

RECOMMEND $100-200M over decade

Planned integrated ground-space exoplanet program
Potentially a rich diversity of habitable planets

<table>
<thead>
<tr>
<th>Branch</th>
<th>Estimate of total galaxy-wide area (billions of Earth area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth-analogues</td>
<td>~2.5</td>
</tr>
<tr>
<td>Tidally locked</td>
<td>~1.3</td>
</tr>
<tr>
<td>Jovian moons</td>
<td>~0.6</td>
</tr>
<tr>
<td>Total</td>
<td>4.4 (2 Earth area per 23 stars)</td>
</tr>
</tbody>
</table>

Predicted Sizes of Different Kinds of Planets

- Pure Iron Planets
- Silicate Planets
- Carbon Planets
- Pure Water Planets
- Pure Carbon Monoxide Planets
- Pure Hydrogen Planets

Seager, Kuchner, et. Al., 2007