The Search for Life in the Universe

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Uniqueness of Earth?

- Sun has sufficient Main Sequence lifetime for life to develop and evolve.
- Sun is a single star.
- Earth has the right *distance* from the Sun, i.e., is in “Habitable Zone”. Limits determined by runaway greenhouse and refrigerator effects.
- Mass of Earth enough to retain large but not too large atmosphere, the greenhouse effect compensates for increasing solar luminosity.
- Has *large moon*, producing tides and stabilizing Earth’s spin axis.
- Jupiter, giant planets removed minor planets and comets from Earth-crossing trajectories, reducing impact rate.
- Jupiter also prevented a planet from forming, resulting in asteroids.
- Solar composition has C/O $< 1$ (0.55), so free oxygen is available.
- The Earth has sufficient Fe to generate sufficient magnetic field to prevent loss of atmosphere, and also prevent oxygen catastrophe.
- The Earth has sufficient water so that upper-mantle convection can lead to plate tectonics, which contribute to climate stability, being an important part of the CO$_2$ cycle.
Future Habitability of Earth

- The Sun brightens as it ages, due to accumulation of He ash in Sun’s core. Also, number of pressure-producing particles decreases ($4H \rightarrow He$). The Sun’s core temperature and density must increase to compensate, resulting in an increase in luminosity.

- Since the Sun was born, its luminosity has increased about 30%.
Search Techniques for Other Solar Systems

- Satellite and space telescope infrared observations (IRAS, HST), of dust emission from protosolar disks.
- Gravitational effects on motion of star due to planets
  - “wobbling” (astrometry)
  - Doppler shifts
- Ground and space-based continuous monitoring of millions of stars (Kepler)
  - Planetary transits
  - Gravitational lensing (microlensing)
- Imaging
  - Speckle imaging especially in infrared with adaptive optics
  - Nulling with interferometry and coronographs
  - Large space-based infrared interferometers (Ex-NPS) for direct imaging
Disks

[Diagram showing a scatter plot with star age on the x-axis and disc brightness on the y-axis, with younger stars on the left and older stars on the right.]

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AST 248, Lecture 22
Gravitational Effects

Radial Velocity Measurements using Doppler Spectroscopy

Observed Period of Star

K

Time (years)

Velocity (m/s)

x displacement (AU)

y displacement (AU)

Gliese 876

center of mass

0.0005 arcsecond

radius of Sun

1960

1965

1970

1975

1980

1990

1995

2005

2010

2015

2020

2025

1998

1999

2000

2020

1995

1990

1975

2005

2015
Limits of Doppler Technique

- Earth
- Jupiter
- Neptune

\[ \log_{10}(p) \]

\[ \log_{10}(M) \]

\[ \log_{10}(a) \]

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Transits

Brief, periodic dimming of star
H₂O also identified
Atmosphere

Graph showing absorption (%) versus wavelength (µm) for different models and observations:
- '+' symbol: Binned model, water + methane
- '+' symbol: Binned model, water + methane + ammonia
- '+' symbol: Binned model, water + methane + CO
- '△' symbol: Observations
- Blue line: Model, water
- Orange line: Model, water + methane

The graph illustrates the comparison between modeled and observed absorption spectra for different atmospheric compositions.
Occultations

Secondary eclipses = occultations

- Occultation: when the planet goes behind the star.
- Small drop in overall flux. Reflected light + thermal emission.
Occultations

- HD189733b: a famous transiting extrasolar planet.
- \( P = 2.2^d, \ M = 1.1 \ M_J, \ R = 1.1 \ R_J \) around a K dwarf star. A classical hot Jupiter.
- Star has a small and faint M dwarf companion.
- Curiously, it is right next (towards) the Dumbbell nebula.
HD189733b is *tidally locked*, i.e. showing the same face towards the star.

It has a hot spot, not exactly facing the star, but somewhat 'behind'. This is due to atmospheric circulation on the planet.
Transmission spectroscopy

- Starlight shining through the planetary atmosphere.
- Note the discovery of Venus' atmosphere during the 1769 transit!
- Planet atmosphere absorbs light in particular wavelengths, depending on its composition!

Figure 6.24: Geometry of transmission (left) and emission spectroscopy (right). During the transit, part of the background star light passes through the (annular) atmosphere of the planet. During the secondary eclipse, there is a switching off of the light reflected or emitted from the day-side surface of the planet.
Circumbinary planets: Kepler-16b

- The first Tatooine (circumbinary planet).
- Star Wars!
- Science is stranger and weirder than fiction (can even think of).
- P=229d
NASA’s Kepler: A Statistical Mission

- Determine the Frequency of Earth-size planets in the habitable zone of sun-like stars.
- Determine the size and orbital period distributions of planets.
- Associate the characteristics of the planets with those of their host stars.
Gravitational Lensing

Brief, one-time brightening of star
Gravitational Lensing

Light Curve of OGLE-2005-BLG-390

Magnification

08 July 28 July 17 August 2005

OGLE
Robonet
Canopus

Danish
Perth
MOA

1.3 1.4 1.5 1.6

1 1.5 2 2.5 3

Source star
Planet
Lensing star
Lensed images
Magnification
Direct Imaging

- Existing methods have inherent limitations
  - Doppler method requires large orbital velocity; small period or orbital radius ($a < 5$ AU)
  - Transit method requires smaller orbit still ($a < 1$ AU)
  - Extracting atmospheric information is indirect and quite difficult
Direct Imaging

- **Existing methods have inherent limitations**
  - Doppler method requires large orbital velocity; small period or orbital radius \((a \leq 5 \text{ AU})\)
  - Transit method requires smaller orbit still \((a \leq 1 \text{ AU})\)
  - Extracting atmospheric information is indirect and quite difficult

- **Direct Detection**
  - Permits direct atmosphere studies with spectroscopy
  - Very difficult: planets are intrinsically faint and very close (in angle) to bright star
  - Detectability greater if in larger orbits \((a > 5 \text{ AU})\)
  - Brightness of planet increases with mass \((> 5 \text{ M}_{\text{Jup}})\)
  - Brightness of Jovian planet greater if very young \((< 10 \text{ Myr})\)
A graph showing the contrast versus age for different masses of Jupiter-like planets, with a focus on the region near the star's habitable zone.
PSF profile – detection limits

- Contrast limit
- Angular separation ("")

- Gemini/Altair
- H-band
- 20% Strehl

- 1-5 Myr massive planets
- Some planets
- Most planets

The graph illustrates the detection limits for different types of planets based on angular separation and contrast.
Technical Challenge

Diffraction from telescope aperture
Currently not a limitation
Could be reduced with coronagraphy

Scattering from atmosphere
Can be compensated by adaptive optics

Scattering from optics
Small defects on optical surfaces
Speckles produced are problematic
What's Been Found

Exoplanets by detection method (July 17, 2015)

Statistics
Total: 1932
Transit: 428
RV: 603
Imaging: 59
Microlensing: 36
Pulsar: 17
Astrometry: 1
TTV: 4
Transit R: 784

Mass (in M_Jup)

Distance to star (in AU)

source: EXOPLANET.EU
What's Been Found
What’s Been Found

[Graph showing distribution of [Fe/H] values]

exoplanets.org | 4/27/2020
What’s Been Found
Hot Jupiters

Hot Jupiters cannot have formed in their present locations.

- No massive planets can form inside the ice-line, since the amount of heavy elements is too small.
- Not enough material available there to form a massive planet.

Inward migration due to

- Slow migration due to momentum transfer from asteroid/comet/dust gravitational scattering, (slingshot or gravity-assist effect).
- Fast migration due to planet-planet gravitational scattering, perhaps ejecting or relocating small planets.
- Kozai cycles: interactions due to an outer massive companion (stellar binary companion), “cold friends”.

Could distinguish these:

- Slow migration dampens inclination
- Planet-planet scattering gives wide range of inclinations
- Outer massive companion also gives wide range of inclination.

About 10% of hot Jupiters have “cold friends” from observations. Hot stars with hot Jupiters have high obliquities.
Overall, Hot Jupiters are Rare
Sizes of Kepler Planet Candidates

As of July 23, 2015

- Super Earth-size: 1,322 (1.25 - 2 R⊕)
- Earth-size: 955 (<1.25 R⊕)
- Neptune-size: 1,592 (2 - 6 R⊕)
- Jupiter-size: 289 (6 - 15 R⊕)
- Larger: 72 (15 - 25 R⊕)
New Kepler Planet Candidates
As of June 2017

Total = 4,034
Candidates in the Habitable Zone
As of February 27, 2012

Size Relative to Earth (Radius)
Equilibrium Temperature (K)

Jun 2010  Feb 2011  Feb 2012

Jupiter  Neptune  Earth
The Multiples

- One: 1425
- Two: 247
- Three: 83
- Four: 28
- Five: 8

Size Relative to Earth

Orbital Period in days
Many planets have too-large radii to explain with cold substances.

Heating could be due to tidal dissipation from

- orbital eccentricity or obliquity (inclination between rotation and spin axes)
- thermal tides
- ohmic dissipation of electrical currents, or
- high atmospheric opacity.
Kepler’s Planets

Planet Sizes

Kepler-7b: 16.52 $R_E$
Kepler-5b: 16.00 $R_E$
Kepler-8b: 15.86 $R_E$
Kepler-6b: 14.79 $R_E$
Jupiter: 11.2 $R_E$

Kepler-9b: 9.4 $R_E$
Kepler-9c: 9.2 $R_E$
Kepler-4b: 3.99 $R_E$
Kepler-9d: 1.64 $R_E$
Earth: 1.42 $R_E$

Kepler-11b: 1.97 $R_E$
Kepler-11c: 3.15 $R_E$
Kepler-11d: 3.43 $R_E$
Kepler-11e: 4.52 $R_E$
Kepler-11f: 2.61 $R_E$
Kepler-11g: 3.66 $R_E$
Composition of Kepler-11 Planets

- **Radius (Earth radius)**
- **Mass (Earth mass)**

- **20% Hydrogen & Helium, 80% Rock**
- **10% Hydrogen & Helium, 90% Rock**
- **100% Water**
- **Earth-like**

Planets:
- **GJ1214b**
- **Kepler-10b**
- **CoRoT-7b**
- **Uranus**
- **Neptune**
- **Earth**
- **Venus**
Recent Successes of Direct Imaging

- GQ Lupi b
- AB Pic A b
- CT Cha b
- DH Tau b
- CHXR 73 (Cha I) b
- 1RXJS J1609-2104 b: A giant planet candidate around a young solar analogue
- HR 8799 bcd: A system of three giant planets
- Fomalhaut b: Optical detection of a giant planet inside a dusty disc
- $\beta$ Pic b: A giant planet at only 8 AU
12-39 Mjup @ ~100 AU

12-13 Mjup @ ~260 AU

12-20 Mjup @ ~440 AU

~12 Mjup @ ~330 AU

~12 Mjup @ ~230 AU

~8 Mjup @ ~330 AU

All of these stars are very young, all companions have large separations
Multi-Planet Detection: HR 8799

Keck JHK-band Summer 2008

Planets are \(\sim 10^4\) times fainter than the star
Fomalhaut
β Pictoris

debris disc

size of Saturn's orbit around the Sun

β Pictoris b

β Pictoris
location of the star

North

East
Planetary Spectra
The Future
<table>
<thead>
<tr>
<th>Pixel / Diameter</th>
<th>Pixel size @ planet (km)</th>
<th>Image</th>
<th>Interferometer Requirements</th>
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<td></td>
<td></td>
<td>Collecting Area</td>
</tr>
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</table>

| 400             | 32                      | ![Image] | IR | 144 km² | 100,000 km |
|                 |                         |       | Visible | 1,296 km² | 5,000 km |

| 100             | 128                     | ![Image] | IR | 0.64 km² | 24,000 km |
|                 |                         |       | Visible | 5.76 km² | 1,200 km |

| 25              | 510                     | ![Image] | IR | 1,024 m² | 6,000 km |
|                 |                         |       | Visible | 9,216 m² | 303 km |

| 10              | 1276                    | ![Image] | IR | 64 m²   | 2,4 km   |
|                 |                         |       | Visible | 576 m²   | 120 km   |