The Search for Life in the Universe
james.lattimer@stonybrook.edu
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→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

The diagram illustrates the relationship between star age and disc brightness. Younger stars are located towards the left of the graph, closer to the 'younger stars' line, while older stars are more towards the right, near the 'older stars' line. The vertical axis represents disc brightness, with 'larger discs' indicating higher brightness compared to 'no disc'. The graph shows that as star age increases, disc brightness tends to decrease.
Gravitational Effects

Radial Velocity Measurements using Doppler Spectroscopy

Observed Period of Star

Time (years)

x displacement (AU)

y displacement (AU)

Gliese 876

Center of mass

0.0005 arcsecond

radius of Sun

James Lattimer

AST 248, Lecture 22
Limits of Doppler Technique

- Jupiter
- Neptune

log mass (Earth mass) vs. log separation (AU)

Doppler detection threshold
Transits

Brief, periodic dimming of star

**HD209458 Transit**

- $P=3.524$ days
- $a=0.046$, $e=0.02$
- $M_{\text{sin}}=0.63$ Jupiter Masses

**Time**

![Diagram of a planet transiting a star](image)
H₂O also identified
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.
Spectrography During Transits

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
Sagittarius Window Eclipsing Extrasolar Planet Search

Hubble Space Telescope • ACS/WFC

James Lattimer

AST 248, Lecture 22
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

OGLE
Robonet
Canopus
Danish
Perth
MOA

8 July 2005
17 August 2005
28 July 2005

April 2001
January 2004

1 1.5 2 2.5 3

1.3 1.4 1.5 1.6

10 Aug. 2005
11 Aug. 2005

Planetary Deviation

Source star
Planet
Lensing star
Lensed images
Magnification

James Lattimer
AST 248, Lecture 22
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

![Diagram showing close and distant planets with transit angles](image-url)
Direct Imaging

- **Existing methods have inherent limitations**
  - Doppler method requires large orbital velocity; small period or orbital radius \((a < 5 \text{ AU})\)
  - Transit method requires smaller orbit still \((a < 1 \text{ AU})\)
  - 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 \((< 10 \text{ Myr})\)
PSF profile – detection limits

Contrast limit vs. Angular separation ("")

1.5 Myr massive planets

Some planets

Most planets

Gemini/Altair
H-band
20% Strehl
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
What’s Been Found

![Plot showing the relationship between planet mass and separation in astronomical units.](exoplanets.org/4/29/2013)
<table>
<thead>
<tr>
<th>[Fe/H]</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.6</td>
<td>1</td>
</tr>
<tr>
<td>-0.4</td>
<td>10</td>
</tr>
<tr>
<td>-0.2</td>
<td>100</td>
</tr>
<tr>
<td>-0.0</td>
<td>1000</td>
</tr>
<tr>
<td>0.2</td>
<td>10000</td>
</tr>
<tr>
<td>0.4</td>
<td>100000</td>
</tr>
</tbody>
</table>

-0.6 -0.4 -0.2 -0.0 0.2 0.4

James Lattimer

AST 248, Lecture 22
What's Been Found

[Graphs showing distribution of planetary radius and planet mass]
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 (1.25 - 2 R_⊕) - 1,322
- Earth-size (<1.25 R_⊕) - 955
- Neptune-size (2 - 6 R_⊕) - 1,592
- Jupiter-size (6 - 15 R_⊕) - 289
- Larger (15 - 25 R_⊕) - 72
New Kepler Planet Candidates
As of June 2017

Total = 4,034
Exoplanet Radii

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 $R_E$

Kepler-10b
1.42 $R_E$

Earth

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

Planets are \(~10^4\) times fainter than the star.
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

Earth’s Atmosphere Through Time

- Escape to space
- Water, H₂, CO
- Steam Atm.
- Impacts
- ?
- CH₄ + other reduced gases
- Temperature
- Ice Ages

Abundance

Time before present, billions of years

- 4.56
- 4.46
- 4.44
- 4.2
- 3.8
- 3.5
- 2.2
- 0.6
- Today

James Lattimer

AST 248, Lecture 22
The Future
<table>
<thead>
<tr>
<th>Pixel / Diameter</th>
<th>Pixel size @ planet (km)</th>
<th>Image</th>
<th>Interferometer Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Collecting Area</td>
</tr>
<tr>
<td>400</td>
<td>32</td>
<td><img src="https://example.com/image1.png" alt="Image" /></td>
<td>IR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Visible</td>
</tr>
<tr>
<td>100</td>
<td>128</td>
<td><img src="https://example.com/image2.png" alt="Image" /></td>
<td>IR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Visible</td>
</tr>
<tr>
<td>25</td>
<td>510</td>
<td><img src="https://example.com/image3.png" alt="Image" /></td>
<td>IR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Visible</td>
</tr>
<tr>
<td>10</td>
<td>1276</td>
<td><img src="https://example.com/image4.png" alt="Image" /></td>
<td>IR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Visible</td>
</tr>
</tbody>
</table>