Extra Solar Planetary Systems and Habitable Zones

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Lecture Overview
Our Galaxy has 200 Billion Stars, Our Sun has 8 planets. It seems like an awful waste if we are alone...

- Exoplanets
  - Definition
  - Detection techniques
  - Space missions
    - Kepler, Spitzer
  - Properties

- Habitable Zones
  - Definition reminder
  - Which stars can host habitable worlds?

What is a Planet?

- IAU Working Group on Extra Solar Planets
  - P. Butler, K. Meech
  - W. Hubbard, F. Mignard
  - P. Ianna
  - M. Kuenster, A. Quirrenbach
  - J. Lissauer, J. Tarter
  - M. Mayor, A. Vidal-Madrid

- Must orbit a star
- $M < 13 M_J$, deuterium burning limit
- $M > 13 M_J$, Brown Dwarf
- $M < 13 M_J$, free floating
- Sub-Brown Dwarf

Planets versus Brown Dwarfs?

IAU definition of a planet:
- Must orbit a star and clear its orbit
- $M < 13 M_J$, deuterium burning limit

Outliers:
- Brown dwarfs: $M > 13 M_J$
- Free floating planets: $M < 13 M_J$

Search for ExoPlanets

Techniques for detection and characterization
- Direct Imaging
- Astrometry
- Radial Velocity
- Transits
- Microlensing
- Disk Warping
- Transmission spectroscopy
- Secondary eclipses

Brightness Problem
- Our planets were known to the ancients, who watched them wander among the stars ... but
- Stars are a billion times brighter than the planet
- Hidden in the glare
**Direct Imaging – Brightness Problem**

**Optical**
- Flux: $F_{\text{sun}} = 10^8 F_{\text{Jup}}$
- Visual magnitude:
  - $V_{\text{sun}} = -26$, $V_{\text{Jup}} = -2.7$
  - $V_{\text{Jup}} = -6 @ 1$ AU

**Infrared**
- Flux ratio is $\sim 10^3$
- Select a specific spectral class to optimize

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**Direct Imaging – Resolution Problem**

Small angle formula:

\[ \theta = \frac{\text{Separation(AU)}}{\text{distance [pc]}} \]

1 radian $= 206265\,''$
1 parsec $= 206265$ AU

- Telescope resolution
  - $\theta = 1.22 \frac{\lambda}{D} \text{ (radians)}$
  - $\theta = 0.26 \frac{\lambda (\mu m)}{D (m)}$
  - $D = 10m, \lambda = 1\mu m, \theta = 0.025''$
  - Shorter $\lambda$, larger $D$

- Atmospheric turbulence
  - Seeing limit $0.5'' - 1''$
  - Adaptive optics

- Telescope support
  - Scattered light (rays, halos)
  - Off-axis telescopes

- $\alpha$ Centauri example
  - $r = 1.35 \text{ pc} = 1.4 \times 10^{16}$ m
  - Jupiter-like planet 5 AU
  - $\theta = 5 / 1.35 = 3.7''$
  - Only 50 nearby stars ok

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**Direct Imaging**

**IR Coronography**
- HR8799
  - Three planet system
  - 10, 10, and 7 $M_{\text{Jup}}$
- $\beta$ Pictoris
  - 0.4'' separation
  - $\sim 8 M_{\text{Jup}}$ at 8 AU
  - $T\sim 1500K$

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**Astrometric Technique**

- Center of Mass [CM]
  - Planet and star orbit barycenter of the system
  - CM of system is usually inside star

- Kepler's 3rd law
  - $P^2 = C a^3$

  \[ P = \text{Period of orbit [yrs]} \]
  \[ a = \text{semimajor axis [AU]} \]

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**Sun's Wobble**

- Combined effect
  - All planets
  - Seen from 10 pc
  - @ dist of $\alpha$ Cen (1.3pc) $CM = 0.004''$

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**Stars' Wobbles**

- Proper motion
  - Stars move relative to the sun due to galactic location

- Parallactic motion
  - Earth orbits the Sun, and star apparent position "loops"

- Exoplanet effect
  - Small disturbances to star proper and parallactic motion

- Astrometric precision
  - Best 0.05'' in single image
  - Can get to 0.001'' from ground

- Problem – long time scale for detection
Radial Velocity

- Star moves back and forth → Doppler shifts
- Spectroscopy detects Doppler shifts → detection of an unseen companion
- Most exoplanets to date have been discovered with this technique
- Precision now less than 1m/s

Radial velocity: Quantities Determined

- Period
- Orbital radius
  - from Kepler’s 3rd law: \( P^2 = C a^3 \)
- Mass
  - actually \( M_p \sin(i) \)
  - only \( v \sin(i) \) known, where \( i \) inclination of orbit
    - \( i = 0^\circ \) face-on, \( i = 90^\circ \) edge-on
- Eccentricity (ellipticity)

Radial velocity method: best candidates

- Planet has small effect on star
  - Planets close to star easier to detect
  - Larger planets easier to detect

What Limits the Radial Velocity Technique?

- Stars can have intrinsic activity
  - “stellar quakes” & oscillations
  - These may be periodic signals
  - Places a fundamental limit on the RV accuracy (at <m/s level)

Transits = Eclipses

- Central transit duration, depends on
  - Stellar diameter
  - Stellar mass
  - Size of planet orbit
  - Inclination (where it crosses star)
- Transit depth → planet size
  - Change in brightness = \( (d_p/d_{\text{star}})^2 \)
  - Probability is low for eclipse
    - only if planet is in line of sight between observer and star
    - But there are many stars . . .

Kepler Mission

- Goals
  - Frequency of terrestrial planets in HZ
  - Frequency of multiple planet systems
  - Distribution of \( a \), albedo, size, mass and density of hot jupiters
  - Properties of stars with planetary systems
- Mission
  - Transit method
  - 372 dy Earth trailing orbit
  - Duration 5-6 years
Kepler Planets

- ~70 confirmed systems
- > 2000 candidates
- Few super-Earths

Transit False-Positives

Astrophysical phenomena that can masquerade as a planetary transit

- grazing eclipsing binaries
- background eclipsing binaries

These require significant amount of ground-based observations to eliminate using radial velocity technique

Kepler 11 – 6 planet system

- Sun like star
- 8 Gy old
- 560 LY from Earth

Transits & Secondary Eclipses

Measure size of transiting planet, one radiation from star transmitted through the planet’s atmosphere

Transmission Spectroscopy

First clear detection of water and methane:

- HD 189733b:
  - hot Jupiter
  - mass 1.15 M_J
  - period 2.2 d
  - semimajor axis 0.03 AU

Swain et al. (2008)
Day and night side of planet

- Andromedae b
- Spitzer telescope obs.
- Temperature difference day – night side: 1400K
- Re-emission faster than global distribution of heat!
- Tidally locked (always same side points to star)

Evaporation of ExoPlanetary atmospheres

HD209458b observations from HST
- detection of an extended hydrogen envelope on (Lyman alpha emission)
- Atm extends > 200,000 km
- H is escaping from planet at 100 km/s
- Planet loses $10^7$ gm/s
- Explains very few detections of planets close to their parent stars

Stratosphere or Carbon-rich?

Uncertainties in model atmospheres lead to uncertainties in chemical composition, and vice versa!

- WASP-12b: C/O ≈ 1?
- very hot Jupiter
- mass 1.4 $M_J$
- radius 1.7 $R_J$
- period 1.1 d
- semimajor axis 0.02 AU
- $T \approx 3000$K
- Not confirmed (2012)

Gravitational Lensing

Einstein’s General relativity
- Foreground star focuses light from distant star
- light of background star temporally enhanced
- Planet additional lensing effect
- Sensitive to small planets
- Immediate success without waiting one period
- But one-time event—statistical information only

Extrasolar Planetary Systems

- 800 exoplanets known within ~500 pc (2013)
- Many objects very close to central star
- Hot Jupiters, Neptunes, super-Earths, etc

Extrasolar Eccentricity Distribution

Most have high eccentricities
- Doesn’t meet Solar System formation expectations
- Need alternate ideas about formation

From: exoplanets.org
Metallicity of host stars

- Planet hosting stars are metal (heavy element) rich
- Consistent with accretion model for giant planet formation
- Higher fraction of heavy elements in disk
- More planetesimals
- Faster planet formation, more likely to have planets

\[ \log(\text{Fe/H}) - \log(\text{Fe/H})_{\odot} \]

Fisher & Valenti (2005)

Hot Jupiter Formation

- In-situ Formation
  - Requires capture 0.7M J gas close to star (unlikely)
- Gravitational scattering
- Perturbations by other planets
- Tidal dissipation with star
- Gas drag and gravitational interactions with protoplanetary disk
  - Difference in forces from inner disk and outer disk
  - No Consensus yet

Examples: Super Earth – Gliese 876

- Discovery 1991-1994
- A. Wolszczan (Penn State)
- Pulsar Survey
- Pulsars – remnant stars
  - Supernova explosion
  - Core is dense enough to form neutron star
  - Conservation angular momentum \( \rightarrow \) spin up
  - Rotation period \( \rightarrow \) millisecond
  - Very strong B field
  - Sweeps past earth, emitting Radio radiation \( \rightarrow \) pulsars
- The Gravitational wobble of star caused by planets
  - Doppler delay / advance in timing of pulses

First 5-Planet System 55 Cancri

<table>
<thead>
<tr>
<th>Mass</th>
<th>Period [dy]</th>
<th>Orbit [10^6 km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-Earth</td>
<td>0.7</td>
<td>2.3</td>
</tr>
<tr>
<td>Jupiter</td>
<td>14.7</td>
<td>17.9</td>
</tr>
<tr>
<td>Saturn</td>
<td>44</td>
<td>35.9</td>
</tr>
<tr>
<td>Saturn</td>
<td>260</td>
<td>116.7</td>
</tr>
<tr>
<td>Jupiter</td>
<td>14 yr</td>
<td>868</td>
</tr>
</tbody>
</table>

Pulsar Planets

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PSR B1257+12 in Virgo

First Extrasolar planet detections
- Not of interest for life . . .
- 3 planets Detected
  - Masses 0.02, 4.3, 3.9M_{Earth}
  - Periods 25, 66, 98 days
- Co-planar orbits
  - Must have formed in a disk

Terrestrial Planet Finder
- Will study all aspects of planets outside our SS
  - Formation & Disks
  - Suitability for life
  - Measurement of Atm composition
- Two phases - TPF-I, TPF-C
- Launch ? (Deferred indef.)
  - Resolved 25x25 pix image of Earthlike planet 10 pc away needs
    - 25 40m telescopes over a 360 km baseline

SIM – Space Interferometry Mission
- Quick facts
  - Earth trailing orbit
    - 5 years, launch 2015???
    - Pushed back 5 times
  - 4 µas accuracy, to mag 20
  - wavelength 0.4-0.9 microns
- Science Goals
  - Determine accurate star positions
  - Planet detection
  - Stellar astrophysics

TPF Resolution

TPF Atmosphere Studies
- R>1000 measurements
- Terrestrial planet atms
- 1 mo of integration
- looking for CH_{4}, N_{2}O

Where were we in 2013?
- As of 4/16/2013: 861 planets
  - 128 Multiple planet sys
  - 567 Hot Jupiters (>0.8 M_{Jup})
  - 52 Super Earths (<10 M_{Earth})
  - >300 Transiting planets
  - 96 Kepler candidates in HZ
  - Masses: 0.001-22.7 M_{Jup}

Our Planet hunting Neighborhood
Most of these planets found in other stars within about 300 light years from our Sun.
Other Planet Finding Missions

- **Gaia – ESA Mission**
  - Launch 2012
  - Map Galaxy to high accuracy (velocity, position)
  - Will discover many planets
- **Darwin (ESA)**
  - Similar to TPF
  - Funding ended in 2007
- **Beyond TPF – Life Finder**