Today  Oct 16  Exoplanets
Comet Siding Spring
Exo-Planet Discovery Methods

- Radial velocity & wobbles:

- Transits:

- Microlensing:
The Kepler Mission

Photometric accuracy
20 parts per million
Radius
Dip = \left( \frac{R_p}{R_{\text{star}}} \right)^2
Kepler candidates
from transits radius, orbital period, inclination & shape

**Eccentricity**

- HD147506b
- $V_{\text{circ}} = 132\ \text{km/s}$
- $\Delta V_f = 24.6\ \text{km/s}$
- $\tau_{\text{ingress}} = 10:36$
- $\tau_{\text{egress}} = 8:37$

- to Earth — $f_0 = 4.64\ \text{rad or 265.4 deg}$

**Impact parameter b**

$$b = a \cos i$$
How to get masses of transiting planets whose stars are too faint for radial velocity

Transit timing variations (TTV)

Interactions of multiple planets result in non-Keplerian orbits

Transit times are not periodic
transit timing variations
transit times vary from predictions due to grav effects from other planets

Kepler 30
(29 Day period)

Fabricky et al 2012
Transit times vary due to strong gravitational interaction between the two close planets.
Kepler 11

Lissauer et al 2011
Doppler shift during transit

(a) rotation is the main cause of line broadening

(b) other broadening mechanisms are also important

Gaudi & Winn (2007)
Rossiter-McLaughlin effect
orbit inclination from doppler shift during transit
Rossiter-McLaughlin effect
orbit inclination from doppler shift during transit
Retrograde orbits!

Albrecht et al 2012
Hot close in planets

Super Earths

Seager 2013
First exoplanet finding – hot Jupiters evidence for migration and stopping

most jupiters are not “hot”
Hot close-in planets

Migration due to disk interactions?

Migration due to grav encounters?

Did hot Jupiters form beyond the snow line?
Many hot jupiter’s have low eccentricity orbits
Hi $\varepsilon$ of esp’s implies that the solar system is very unusual

Median $\varepsilon \sim 0.3$

Origin
- planet-planet interaction?
- planet-disk interaction?
- brown dwarf companion?

Migration effect
Tidal circularization

![Graph showing eccentricity vs. period with data points and annotations.](image)
Moderately elliptical exoplanet orbits are common.
Single Jupiters
Typically hot or near 3AU

Multi planet systems
~ devoid of hot Jupiters

Multi planet systems commonly lower eccentricity
Orbital circularization
Why most planets very close to stars have circular orbits

(typical exoplanets not close to stars have $e = 0.3$)
This implied - typical stars with planets are rich in heavy elements supported the core-accretion formation of Jupiter-mass planets.
M > 1M$_{\text{jup}}$

M < 0.1 M$_{\text{jup}}$

metallicity not important for low mass planets
Metal content influences large planet formation but not small ones.
Puffed up Jupiters

totally unexpected
Super Earths/ Mini Neptunes

Totally unexpected

The most common planets

Many are close-in
MiniNeptunes a totally new class of object
Remarkable Exoplanet Findings

Planets are common ~ most stars have planets

Hot Jupiters - evidence for planet migration
Hot Jupiters - commonly are alone
Hot Jupiters – most common for metal rich stars

Common planetary systems have close in planets – unlike solar system

Most common planets -super Earth’s/MiniNeptunes – unlike solar system

Planets in orbital resonance – evidence for planet migration

Puffed up (low density) Jupiters

Planets commonly have higher eccentricity orbits than SS

Inclination of orbits is broad including retrograde
varies with star type and mass

Planet systems are often “packed”

diverse planet systems
Planets $<2.8R_E$ are found within 0.25 AU of 30-50% of Sun like stars!

Howard et 2013 Science
Sizes of Planet Candidates
Totals as of November, 2013

- Super Earth-size (1.25 - 2 Rₐ) - 1,076
- Earth-size (< 1.25 Rₐ) - 674
- Neptune-size (2 - 6 Rₐ) - 1,457
- Jupiter-size, (6 - 15 Rₐ) - 229
- Larger, (> 15 Rₐ) - 102
Planets are common ~ most stars have planets

Hot Jupiters - evidence for planet migration
Hot Jupiters commonly are alone
Hot Jupiters – most common for metal rich stars

Common planetary systems have close in planets – unlike solar system

Most common planets appear to be super Earth’s – unlike solar system

Planets in orbital resonance – evidence for planet migration

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Exoplanet Atmosphere Compositions

Star + Planet

Combined Spectrum

Star

Eclipse Spectrum

Planet

Planet Spectrum

Isolating a Planet's Spectrum
a. Starlight entering the atmosphere of a planet.
b. Starlight passing through a thin atmosphere.
c. Starlight passing through a dense atmosphere with clouds.
IR emission spectrum from secondary eclipse

Seager & Deming 2010
Transmission spectra - 1000K hot Jupiter
The Habitable Zone concept

Not too close
Not too far
The search for goldilocks planets
HZ - The Habitable Zone

An important, widely used term
A major performance metric for planet searches
Some times misused or overly simplified (probably)
Not perfectly defined or known

Note: Earth was in the HZ for 4Gy before the Cambrian explosion

Definitions from the web

1. a region around a star where the physical conditions on planets in the region are conducive to life

2. the region around a star where an Earth-like planet can maintain liquid water on its surface.

3. zone around a star in which water is in the liquid form (273-373 K)

4. habitable zone (HZ) is a region of space where conditions are favorable for the creation of life

5. an imaginary spherical shell surrounding a star throughout which the surface temperatures of any planets present might be conducive to the origin and development of life as we know it.
Gliese 581 - the difficulty of finding a home for life