From Planet Detection to Planet Parameters

Michael Perryman

Heidelberg (ZAH/MPIA), currently University of Bristol

Heraeus Conference, 6 June 2011
Planet Detection Methods

- Photometry
- Imaging
- Microlensing
- Astrometry
- Timing (ground)
- Radial velocity
- Pulsars
- Sub dwarfs
- Binary

Survival
- masses, Δi for multiples
- masses × sin i, resonances
- unbiased host star statistics
- magnetospheres
- sizes, densities, atmospheres

Decreasing planet mass

- Existing capability
- Projected (10–20 yr)
- n = planets known
- Discoveries
- Follow-up detections

Total: 494 planets
November 2010

Discovered:
- 10 planets
- 358 planets
- 11 planets
- 12 planets
- 103 planets

Detected:
- 10 planets (6 systems, 3 multiple)
- 461 planets (390 systems, 45 multiple)
- 4 planets
- 11 planets (10 systems, 1 multiple)
- 12 planets (10 systems, 1 multiple)
- 108 planets (7 systems, 1 multiple transit)

Monday, June 6, 2011
Topics

- radial velocities
- astrometry
- transits
- internal structure and composition
- radio emission
- population synthesis
The distribution of multiple systems

increasing host star mass

Monday, June 6, 2011
Numerous of these multiple systems are in resonance...

An object’s mean motion, \( n \equiv \frac{2\pi}{P} \)

mean motion resonances \( (P_1/P_2 \sim i/j): \)

- 2:1, 3:1, 4:1, 5:1, 5:2, etc

Many other types of resonance...

- spin-orbit
- tidal locking (1:1)
- Mercury (3:2)
- Kozai resonance (\( e \) versus \( i \))
- Lagrange (1:1) resonance
- retrograde resonances...

For a heuristic physical description, see Peale (1976), ARA&A 14, 215
Mean motion resonances come in many different flavours, e.g. for the 2:1

1. Unstable 2:1
   - Conjunctions at pericentre

2. Stable 2:1 (aligned)
   - Conjunctions at apocentre
   - Conjunctions at pericentre

   Or

2a. Apsidal libration
   - Apsidal libration (small libration angle ⇔ deep resonance)

2b. Apsidal corotation
   - Apsidal alignment rotates (usually with libration)

3. Stable 2:1 (anti-aligned)
   - Conjunctions anti-aligned

4. Stable 2:1 (asymmetric)
   - Asymmetric apsidal configuration
   - Both may corotate and/or librate
... and the first triple (Laplace) resonance

(a) Galilean satellites of Jupiter

$$n(\text{Io}) - 3n(\text{Europa}) + 2n(\text{Ganymede}) = 0$$

... to 9 significant digits, Peale (1976), ARA&A 14, 215

(b) GJ 876 planets b, c, e

Question: how do planets get into resonance?

Answer: differential (convergent) migration in the residual gas disk

Sándor et al (2010), A&A 517, A31
Topics

- radial velocities
- astrometry
- transits
- internal structure and composition
- radio emission
- population synthesis
Astrometry...

\[ \alpha = \frac{M_p}{M_\star + M_p} a \approx \frac{M_p}{M_\star} a \]

\[ \approx \left( \frac{M_p}{M_\star} \right) \left( \frac{a}{1 \text{ AU}} \right) \left( \frac{d}{1 \text{ pc}} \right)^{-1} \text{ arcsec} \]

Effect on the star’s motion around the barycentre

But the size of the effect is small...

Monday, June 6, 2011
v And observed with the Hubble Space Telescope Fine Guidance Sensors

radial velocity orbit + astrometric displacement = orbit inclination

gives a (large) mutual inclination between planet orbits of $\Delta_{cd} = 29.9$ deg


Important for determining statistics of co-planarity, as inputs to theories of formation and dynamical stability (in future: Gaia, PRIMA)
Planet mandalas...
.. and the nature of the solar dynamo

... exoplanets may allow verification whether angular momentum changes are responsible for some of the solar activity modulations
Topics

- radial velocities
- astrometry
- transits
- internal structure and composition
- radio emission
- population synthesis
Transits

The transiting systems have proven of great importance:

- for densities from absolute masses + accurate radii
- atmospheric probes from transits and secondary eclipses
Transit photometry: example state-of-the-art

...from the ground, using ULTRACAM
Bento et al 2011, in preparation

...from space, using CoRoT
Snellen et al (2009), Nature 459, 543
Principle of transmission & emission spectroscopy

Transit: transmission = A − B

Secondary eclipse: emission = C − D

Area of planetary atmosphere intercepted: annulus of width \( \sim 5H \), where

\[
H = \frac{kT}{\mu m g_p}
\]

Many results (e.g. Spitzer) from, notably HD 209458 and HD 189733:

H, H₂O, CO₂, CH₄, Na, etc
Other transit examples...

WASP–1 2.520 d
WASP–2 2.152 d
XO–1 3.942 d
HAT–P–1 4.465 d
HAT–P–2 5.633 d
HAT–P–3 2.900 d
HAT–P–5 2.788 d
HAT–P–6 3.853 d
GJ 436 2.644 d

Torres et al (2008)
ApJ 677, 1324
Higher-order effects

• from transit light-curve:
  • stellar density, $\rho^*$
  • planet surface gravity, $g_p = \frac{GM_p}{R_p}$
  • planet limb darkening

• higher-order photometric effects:
  • planet: satellites, rings/comets, planet oblateness, rotation, weather, bow shocks
  • star: spots, effects of rapid rotation, ellipsoidal variations

• higher-order spectroscopic effects:
  • projected angle between stellar spin axis and planet orbit (Rossiter-McLaughlin)
  • effects of atmospheric opacity, atmospheric winds

• higher-order timing effects:
  • apsidal precession due to tidal bulges, rotational flattening, general relativity
  • nodal precession in the case of polar orbits (WASP-33)
  • effects of planet satellites
  • effects of other planets, including Trojans
  • perspective effects due to star’s parallax and proper motion
  • magnetic breaking, non-gravitational forces (Yarkovsky effect)
Rossiter-McLaughlin effect

\[ b = -0.5, \lambda = 0^\circ \]
\[ b = -0.5, \lambda = 30^\circ \]
\[ b = -0.5, \lambda = 60^\circ \]

\[ \text{Relative flux} \]

\[ \text{Radial velocity (m s}^{-1}) \]

\[ \text{Time since mid-transit (d)} \]

\[ \text{HD 189733} \]


- some orbits are retrograde
- or scattering + migration: Marchi et al (2009), MNRAS 394, L93
- but not migration alone
Other transiting phenomena observed...

![Graph of HD 189733](image)

**star spots:** Pont et al (2007)

**ellipsoidal effects:** Welsh et al (2010)

- Kepler-11 has 6 transiting planets, with periods of 10, 13, 22, 32, 47, and 118 days
.. and which may be observable...

perspective effects
(Rafikov 2009, Scharf 2007)

Transit geometry from 2d interferometry
(van Belle 2008: PASP, 120, 617)

close-in, spun-up systems
(Pont 2009: MNRAS 396, 1789)
These transiting systems are extreme laboratories:

- Densities are as low as 0.09 Mg m\(^{-3}\) (WASP-17)
- Shortest orbital periods of 0.79 day (WASP-19)
- The stellar disk subtends up to 35 degrees (WASP-12)
- Longest orbital period (with \(e = 0.93\)) is 111 day (HD 80606)
- Some orbits are highly misaligned or retrograde
- Extreme tidal bulges, up to 70 km
- High relativistic apsidal and nodal precession (WASP-33)
Topics

• radial velocities
• astrometry
• transits
• internal structure and composition
• radio emission
• population synthesis
Several areas of exoplanet research require estimates of composition versus temperature and pressure (agglomeration during formation, modeling interiors and bulk properties, formation of atmospheres, etc).

1. start with a certain initial elemental composition (e.g. assumed solar nebula composition)
2. assume time for the relevant chemical reactions to reach equilibrium at given T and P
3. use thermodynamic equilibrium calculations to predict gas/gas-grain/solid phase reactions
4. predict which gases form, which elements or compounds condense, and in which proportions

Classification of solar system bodies into four compositional types: terrestrial, gas giants, ice giants, and dwarf planets (Lodders 2010, Exoplanet Chemistry)
Effect of gravity on shape and structure versus mass

- Sun
- 80 M\(_J\) : hydrogen fusion
- 13 M\(_J\) : deuterium fusion
- Jupiter
- 13 M\(_J\) : degeneracy pressure
  \[ \sim \text{Coulomb pressure} \]
- Uranus
- Earth
- Mars
- Moon
- Ceres
- Pallas
- Miranda
- Hyperion
- Comet Tempel 1

Density (Mg m\(^{-3}\))

Object mass (kg)

Physical process
- convection important
- compression important
- chemistry modified
- gravity \(\Rightarrow\) sphericity
- gravity \(\Rightarrow\) cohesion
Mass versus radius
(a powerful diagnostic of interiors)


Chabrier et al (2009), AIP Conf 1094, 102

ternary diagrams
**Interiors and atmospheres: hydrogen**

![Diagram showing temperature and pressure relationships for hydrogen phases.](image)

Guillot (2005), AREPS, 33, 493

---

**Notes:**

* molecular-metallic transition
* solidification possible at low $T$ and high $P$, but relevant for an isolated Jupiter only after $\sim 1000$ Gyr of cooling (Hubbard 1968)
* $P-T$ profiles for solar system giants and HD 209458
19 solid phases: ice XII discovered in 1996, XIII-XIV in 2006, and XV in 2009
16 crystalline polymorphs: hexagonal, cubic, monoclinic, orthorhombic, tetragonal...
densities are <1 for Ih/Ic only, and reach 2.5 for ice X
ice VII (and perhaps X/XI) are most relevant for planetary interiors (Valencia et al 2007)

(properties collated by the International Association for the Properties of Water and Steam)
For a 6M\textsubscript{Earth} ‘ocean planet’ in the habitable zone with $T_{\text{surface}} = 7\,\text{C}$, Leger et al (2004, Icarus 169, 499) derived:
ocean depth = 45−72 km (isothermal-adiabatic)
Topics

- radial velocities
- astrometry
- transits
- internal structure and composition
- radio emission
- population synthesis
Radio emission

Five of the solar system planets with dynamo-driven magnetic fields produce low frequency (cyclotron) emission. So far, no exoplanets....
Topics

- radial velocities
- astrometry
- transits
- internal structure and composition
- radio emission
- population synthesis
Planet formation: 
growth by 14 orders of magnitude 
(in one viewgraph)

Time scale 
(year) 

10^3? 

10^4 10^5 10^6 ?? 10^7 10^8 

Body 
dust 
rocks 
planetesimals 
proto- 
planets 
terrestrial 
planets 
gas 

Inner 
disk 

particle agglomeration 
(settling and radial migration) 

mechanism 
particularly uncertain 

pairwise collisional 
growth or 
Goldreich-Ward 
fragmentation 
runaway 
growth 
oligarchic 
growth 
post- 
oligarchic 
(chaotic) 
growth 
core accretion or 
gravitational instability 

Outer 
disk 

10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 
diameter (m) 

1 km 10 km 100 km 1000 km 10 000 km 100 000 km 

Body 
dust 
rocks 
planetesimals 
proto- 
planets 
terrestrial 
planets 
gas 

Inner 
disk 

particle agglomeration 
(settling and radial migration) 

mechanism 
particularly uncertain 

pairwise collisional 
growth or 
Goldreich-Ward 
fragmentation 
runaway 
growth 
oligarchic 
growth 
post- 
oligarchic 
(chaotic) 
growth 
core accretion or 
gravitational instability 

Outer 
disk 

10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 
diameter (m) 

1 km 10 km 100 km 1000 km 10 000 km 100 000 km 

Monday, June 6, 2011
there are enough planets that a statistical approach to model results is now possible  
Just published - topics covered:

1. Introduction
2. Radial velocities
3. Astrometry
4. Timing
5. Microlensing
6. Transits
7. Imaging
8. Host stars
9. Brown dwarfs
10. Formation and evolution
11. Interiors and atmospheres
12. The solar system
The End