III

The properties of extrasolar planets
(as of early 2016)

http://sgoodwin.staff.shef.ac.uk/phy229.html
3.0 Introduction

This lecture will discuss what we have found so far.

It is important to remember that all detection methods have selection effects and biases:
   We can only find what we are capable of finding,
   We can only find planets around stars we are observing.

The data can only be interpreted with these things in mind.

This is for data extracted from exoplanet.eu on Feb 2\textsuperscript{nd} 2016.
In 1995 Mayor & Queloz discovered a roughly Jupiter mass planet around 51 Peg using the Doppler method.
3.1 A `hot Jupiter'

51 Peg planet: $M \sin i = 0.468 \ M_{\text{jup}}$
period = 4.231 days
eccentricity = 0.00

The period implies a semi-major axis of 0.052 au (Mercury is 0.387 au)

Completely unlike anything in the Solar System and totally unexpected – named a `Hot Jupiter'.
3.2 Selection effects and biases

Why only use a subset of planets?

Each method has different selection effects, a vitally important issue in astronomy is to deal with selection effects and biases properly.

Many naked-eye stars are giants so you could make the mistake of thinking they are common. They aren't – they're just very bright and so easy to see (Malmquist bias).

We need a homogeneous dataset and we need to understand the selection effects and biases in that dataset.

Next is a figure with all planets for which we have an estimate of semi-major axis and planetary mass. Note that some masses are minimum masses, some are dynamical, some are guesses, some are from colours...
3.2 Selection effects & biases

All planets semi-major axis vs. planetary mass...

- Direct detection
- Doppler and/or Transit
- Pulsar planet
3.2 Selection effects and biases

The Doppler and Transit methods are the best to pick:

- you get lots of information on the planets.

- periodic radial velocity variations from a planet are difficult to 'fake', pulsations or star spots will change the star's colour.

- selection effects and biases are relatively well known (difficult one to factor-in is changes with technology and observing time with time).

- potential problem is also which method detected the planets first (initially Doppler first, now lots of Transit firsts).
3.2 Selection effects & biases

This means that we have the following selection effects:

The Doppler/Transit method will find things that:

a) are relatively massive or large (compared to the star).
b) are close to the star (rv and P drop with a by Kepler's laws).
c) are around a star that is being observed...
3.3 Masses

cf. Solar System: Saturn 0.30, Uranus 0.046, Earth 0.003
3.3 Radii

cf. Solar System: Saturn 0.84, Uranus 0.36, Earth 0.09
3.3 Masses & Radii

Note that the previous two plots contain slightly different data. Masses are not always available for Transit planets, and radii only for those that Transit.

Most planets are around $1 \, M_{\text{Jup}}$ in mass: the Doppler method is strongly biased to higher mass planets.

Radii span a large range – a peak at about a Jupiter radius for gas giants that Transit, but a significant peak at $0.2 \, R_{\text{Jup}}$ for ice giants and superearths. Transits are not bad at finding low-radius planets (note the tail down at Earth radius).

Low-mass planets tend to be found by Transit first and then a Doppler follow-up.
3.3 Masses & Radii

If we include selection effects (massive/large planets are easier to find) then this suggests that low-mass/radius planets are very common: they are the most difficult to find, but we still find quite a few of them.

The true planet mass distribution could be a power-law to low masses. Or it could peak in the superearths (are these the most common type of planet?).
3.3 Masses

There is one outlier:

Kepler-138b is Mars-sized with a mass of $0.00021 \, M_{Jup}$ ($0.07 \, M_{\text{earth}}$) in a ~10 day orbit.

This shows the power of Transits to detect very small planets (this was around a $0.6 \, M_{\text{Sun}}$ M1 dwarf star, so slightly easier to see than around a G dwarf).
3.4 Orbital separations

cf. Solar System: Mercury 0.39, Earth 1.00, Jupiter 5.2, Neptune 30.1
3.4 Orbital separations

Semi-major axes tend to be low. Transits are almost all low-period planets (most are Kepler with only a few year baseline).

Doppler now has a baseline of 25 years (first observations around 1990), but sensitivity has improved significantly in that time. This takes us to almost 10AU (but it would have to be massive to give a signal at 10AU).

It is clear that massive planets in close orbits are common.

It is becoming clear that low-mass planets in close orbits are common.

Presumably, massive planets in distant orbits are also common, but this is less clear due to the selection effects.
3.4 Eccentricities

cf. Solar System: $e < 0.2$ (Mercury 0.2, Mars 0.1, Gas Giants around 0.05).

Most planets are in roughly circular orbits, but some quite extreme eccentricities are found at almost all separations (very close orbits will be circularised by tidal interactions).
3.4 Stellar mass

Observer bias!

We can only see planets around stars we observe. Most observations have been of G dwarfs – hence that is where most planets have been found.
3.4 Stellar metallicity

Is there a metallicity-planet mass correlation? How much is observer bias?

We might expect planet masses to depend on metallicity – there is a vague Correlation, but nothing significant...
3.4 The brown dwarf desert

Close (<5 AU), very high-mass planets or brown dwarfs should be easy to find, but are rare. There are not insignificant numbers of close stellar companions, and plenty of planets, but a lack of close brown dwarfs.
3.4 Densities

Transit + Doppler gives density
(Earth $0.1 \, R_{jup}$, $0.003 \, M_{jup}$)
The line on the graph above is for constant density.

Terrestrial planets are 3 to 5 g/cc: mostly iron and silicates (rocks).
Ice Giants are >1 to 2 g/cc: mostly volatiles.
Gas Giants are ~1 g/cc: mostly H and He.

Note that densities are increased by gravitational compression in massive planets so are not quite a direct measure of composition.

Be careful with outliers on this figure: some masses are very uncertain or upper/lower limits, so some of these densities are not very reliable.
3.5 What have we found?

0. Planets are common.

1a. Hot Jupiters are common.
   b. Increasing evidence that 'normal' Jupiters are also common.

2a. There appear to be more planets at lower-masses (power-law?).
   b. Evidence that Earth-mass planets are common.

3. Most planets are in roughly circular orbits (but moderate eccentricities are not uncommon).

4. Brown dwarfs close to stars are very rare (but stars and planets aren't).

5. Is there a lack of planets (and lower mass planets) at low metallicity?
Most planets have been found using the Doppler and/or Transit method. This means they tend to be massive and close to the star. We have to be very careful when drawing conclusions from the current planet sample to take into account the inherent selection effects and biases.

Numbers of planets seem to increase with decreasing mass.

There is a 'brown dwarf desert': a lack of brown dwarfs close to stars which would have been found by the Doppler method if they existed.

We tend to find planets around Solar-type stars of Solar metallicity – but this is where we tend to look!

We must be careful when including other samples as they have different selection effects.