Lecture 1: Observations of planetary systems

For centuries the study of planet formation essentially amounted to trying to understand how the Solar System formed, but in the last 15–20 years the discovery of large numbers of planets around other stars have revolutionised this field. We are now able to study the Solar System in exquisite detail, but are also able to obtain large number statistics from surveys of exoplanets. In this course we aim to look at planet formation from an astrophysical perspective (rather than a planetary science one), and so will consider both Solar System and exoplanet data in turn. In practice these data are complementary, and a successful theory of planet formation should be able to explain the observed properties of both the Solar System and extra-solar planetary systems.

1 The Solar System

We reside in our own planetary system, and much of what we know about planets and their origin comes from observations of the Solar System. The Solar System comprises the Sun, eight planets, and a large number of smaller bodies (including "dwarf planets", asteroids, comets, etc.). The eight planets can be divided into three different types:

- **Gas Giants:** Jupiter & Saturn. These planets are massive (hundreds of times more massive than Earth), and are composed primarily of hydrogen and helium. However, they have solid cores ($\sim 10\mathrm{M}_\oplus$), and by comparison to the Sun are substantially enriched in heavy elements.
- **Ice Giants:** Uranus & Neptune. Composed primarily of heavier molecules, principally H_2O, NH_3 & CH_4, along with low-mass ($\sim 1\mathrm{M}_\oplus$) solid cores.
- **Terrestrial Planets:** Earth, Venus, Mars & Mercury. These are low-mass rocky planets, with molten cores.

The dynamical properties of the planets also provide useful clues as to their origin. All eight planets are nearly co-planar (with relative inclinations $< 10°$), and all but Mercury have small (< 0.1) eccentricities. Six of the eight planets rotate in the prograde direction (with respect to their orbits); Venus has retrograde rotation, while Uranus' rotation axis is inclined by 98° to that of its orbit. The near-perfect co-planarity of the Solar System planets strongly suggests formation from a single rotating disc. (This is the so-called Nebular Hypothesis, first suggested in the 18th century by Kant, Laplace and others.)

If we consider the Solar System's rotation, we see that the planets account for the majority of the Solar System's angular momentum. We can estimate the Sun's angular momentum by assuming that it rotates as a solid body, so

$$J_\odot = k^2 M_\odot R_\odot^2 \Omega_\odot \,, \tag{1}$$

with the constant $k^2 \simeq 0.1$. For a Solar rotation period of 25 days, this gives $J_\odot \sim 3 \times 10^{48}$g cm^2 s^{-1}. By comparison, the orbital angular momenta of Jupiter and Saturn are:

$$J_{\mathrm{Jup}} = M_{\mathrm{Jup}} \sqrt{G M_\odot a_{\mathrm{Jup}}} \simeq 2 \times 10^{50} \mathrm{g\,cm^2\,s^{-1}}. \tag{2}$$

$$J_{\mathrm{Sat}} = M_{\mathrm{Sat}} \sqrt{G M_\odot a_{\mathrm{Sat}}} \simeq 8 \times 10^{49} \mathrm{g\,cm^2\,s^{-1}}. \tag{3}$$

The planets therefore account for $> 99\%$ of the total angular momentum of the Solar System, with Jupiter dominating the overall angular momentum budget. By contrast, the planets contain only 0.13% of the total mass of the Solar System.

Radioactive dating of the Solar System is its own sub-field, and is beyond the scope of this course. However, we note in passing that radioactive dating of primitive meteorites (chrondites) measures the age of the Solar System to be 4.57Gyr. More interesting for understanding planet formation are the *relative* ages of the various bodies in the Solar System, but this is much more challenging (and subject to significant systematic uncertainties).

Much more detailed discussion of the Solar System is possible, but our focus here is on the astrophysical nature of planet formation. However, even from this simple discussion we can see that planet formation is a very challenging problem. In order to form the Solar System planets, solid bodies must grow from the sub-μm dust grains found in the ISM to Earth-sized objects: an increase of at least 12 orders of magnitude in size, or approximately 40 orders of magnitude in mass. In addition the process(es) of planet formation must efficiently separate mass from angular momentum, and preferentially retain heavy elements.

2 Methods for detecting exoplanets

The first planets detected around a star other than the Sun were the pulsar planets (Wolszczan & Frail 1992), but despite intensive subsequent study only a handful of these unusual objects have been found. The first planet around a main sequence star, 51 Peg b, was discovered by Mayor & Queloz in 1995, using radial velocity observations[1]. We now have several different techniques for detecting extra-solar planets, and here we summarize the most successful[2].

2.1 Direct Imaging

The most straightforward means of detecting exoplanets is via direct imaging. However, the faintness of the planets, and the extreme contrast between the star and planet(s), make it one of the most challenging methods of exoplanet detection. The first direct images of planetary-mass objects around main sequence stars were made by Marois et al. and Kalas et al. in 2008, but to date relatively few direct imaging detections have been made.

At optical wavelengths most of the emission from planets is reflected starlight. A planet of radius R_p at orbital radius a reflects a fraction

$$f = A\frac{\pi R_p^2}{4\pi a^2} = 4.6 \times 10^{-10} \left(\frac{A}{1.0}\right) \left(\frac{R_p}{R_\oplus}\right)^2 \left(\frac{a}{1\mathrm{AU}}\right)^{-2} . \tag{4}$$

Here A is the albedo (typically $A = 0.1$–0.5). If we assume that $A = 0.3$ we find that Jupiter reflects $f_{\mathrm{Jup}} \simeq 6 \times 10^{-10}$ of the Sun's luminosity, while Earth reflects $f_\oplus \simeq 1 \times 10^{-10}$. We therefore expect planets to be 22–25 mag fainter than their host stars at optical wavelengths.

This presents two problems: brightness and contrast. Planets around even nearby stars are very faint, and large telescopes are necessary simply to reach the sensitivity required to detect them[3]. The contrast problem is even more severe. At a distance of 10pc a physical separation of 1AU subtends an angle of $0.1''$, so direct imaging of giant planets requires > 20 mag of dynamic range at sub-arcsecond separations. This can only be achieved by using coronographic techniques to block the light from the central star, but even in this case the residual point-spread function (PSF) artefacts can be orders of magnitude brighter than the planetary targets. The most successful method (to date) of overcoming this problem is so-called Angular Differential Imaging, where many images are taken while the sky is allowed to rotate in the image plane. PSF artefacts therefore rotate with respect to the sky, allowing real sources to be identified. Other techniques, such as apodizing phase plates and aperture-masking interferometry, have been successful at infrared wavelengths (where the contrast problem is not so severe), but until recently even the best systems are unable

[1]Several earlier detections, such as HD114762b (Latham et al. 1989), obtained minimum masses ($M_{\mathrm{p}} \sin i$) that were in the regime we might consider "planetary", though most were described as brown dwarfs at the time. However, 51 Peg b was the first object around a main sequence star which was unambiguously shown to be of planetary mass.

[2]For reasons of space we will not discuss gravitational microlensing or timing methods in detail.

[3]Detecting a point source of magnitude $V = 26$ requires an integration of $\sim$1 hour on an 8m-class telescope.

to reduce the stellar emission sufficiently within $\lesssim 0.5''$. To date, therefore, direct imaging detections have largely been limited to luminous (super-Jupiter) planets around nearby ($\lesssim$ 40pc) stars at large ($>$ 10AU) separations. However, the last few years have seen the advent of new instruments [such as the Gemini Planet Imager (GPI), and SPHERE on the VLT] which are capable of resolving planets at separations down to $\sim 0.1''$. Over the next few years these should deliver a complete census of giant ($\gtrsim$M$_{\rm Jup}$) planets around nearby stars down to separations $\sim$ 10AU.

2.2 Radial Velocity Searches

Until the launch of the *Kepler* satellite, the method which accounted for the largest number of exoplanet detections uses Doppler spectroscopy to measure stellar radial velocities. In a planetary system the host star undergoes "reflex" motion about the system's barycentre, and repeated measurements allow planets to be detected via periodic variations in the star's radial velocity.

If we consider a planet of mass $M_{\rm p}$ orbiting a star of mass M_* at radius (semi-major axis) a, we can calculate the magnitude of the RV signal. For simplicity, we consider the case of a circular orbit. In the limit $M_{\rm p} \ll M_*$ the planet's orbital speed is simply the Keplerian velocity

$$v_{\rm K} = \sqrt{\frac{GM_*}{a}}\,, \tag{5}$$

and conservation of momentum requires that $M_* v_* = M_{\rm p} v_{\rm K}$. If the orbital angular momentum is inclined at an angle i to the line-of-sight then the stellar radial velocity varies sinusoidally with (half-)amplitude

$$K = v_* \sin i = \frac{M_{\rm p} \sin i}{M_*}\sqrt{\frac{GM_*}{a}}\,. \tag{6}$$

The orbital period P is also Keplerian

$$P = 2\pi\sqrt{\frac{a^3}{GM_*}}\,, \tag{7}$$

and both P and K are therefore directly observable quantities[4]. The required observational precision is straightforward to estimate, and for a 1M$_\odot$ host star we find

$$K = 28.4\,{\rm m\,s^{-1}}\left(\frac{M_{\rm p}\sin i}{1{\rm M_{Jup}}}\right)\left(\frac{a}{1{\rm AU}}\right)^{-1/2}\,. \tag{8}$$

Detecting a Jupiter-like planet therefore requires $<$ 10m s^{-1} precision, while $<$ 10cm s^{-1} precision is required to detect Earth-like planets. Moreover, we must observe for roughly the orbital period in order to obtain a detection. RV searches are therefore biased towards massive planets in short-period orbits, with high line-of-sight inclination angles (i.e., viewed close to edge-on). In practice we usually cannot determine the inclination angle i, so we instead measure $M_{\rm p} \sin i$ (a lower limit to the planet's true mass).

Most of the early RV detections were massive ($\gtrsim$M$_{\rm Jup}$) planets in short-period ($<$ 5 day) orbits, and these are usually referred to as "hot Jupiters". Their existence presented an immediate challenge to our understanding of planet formation (as they exist well inside the radius at which solids would sublime), and sparked a great deal of interest in the theory of planet migration. Subsequent RV observations have conducted detailed surveys of essentially all of the F-, G- and K-type stars in the solar neighbourhood (out to $\sim$ 20pc), with 10–20m s^{-1} precision over a period of approximately 20 years. These surveys are therefore complete for giant planets ($\gtrsim$M$_{\rm Jup}$) with

[4]It is possible to generalise this analysis to the case of eccentric orbits. In this case the velocity amplitude K is multiplied by a pre-factor $1/\sqrt{1-e^2}$, and the RV curve is no longer sinusoidal.

periods $\lesssim$5–10yr. Newer spectrographs (such as HARPS & HIRES) have attained precisions of $\lesssim$1m s^{-1}, and are sensitive to Earth-mass planets in short-period orbits, but surveys with these instruments have a shorter time baseline (and limited sampling) and therefore only offer good statistics for periods $\lesssim$5yr. It is not clear, however, how much further RV methods can be pushed. Stellar variability and activity ultimately limits the precision with which Doppler measurements can be made, and although this floor has not yet been reached, with current technology it seems unlikely that precisions $\ll$1m s^{-1} are possible for large numbers of stars. Nevertheless, over 500 planets have now been discovered using RV methods, and this sample remains the major source of our statistical knowledge of exoplanets for periods $\gtrsim$100 days. "Follow-up" RV measurements are also our primary means of measuring the masses of planets discovered via other methods.

2.3 Transit Methods

A transit occurs when a planet passes between its host star and the Earth. It is straightforward to compute the dimming fraction f, which to first-order (neglecting limb-darkening and grazing transits) depends only the relative radii of the star and planet:

$$f = \frac{R_{\rm p}^2}{R_*^2}\,. \tag{9}$$

For Jupiter this gives $f_{\rm Jup} \simeq 0.01$, while for Earth we find $f_{\oplus} \simeq 10^{-4}$. We therefore see that detecting transits requires a high degree of photometric precision: for bright host stars these correspond to $\sim$ 10mmag for gas giants, and $\lesssim$ 0.1mmag for rocky planets. Giant planet transits are therefore detectable with ground-based telescopes, but the variability induced by our atmosphere means that transits of Earth-like planets can only be detected from space.

The probability of observing a transit in any given planetary system is small, as the stellar orbit must be observed almost perfectly edge-on for a transit to occur. We see a transit if

$$\cos i \le \frac{R_{\rm p} + R_*}{a}\,, \tag{10}$$

so if an ensemble of planetary systems has a random distribution of inclination angles the probability of observing a transit is

$$p = \frac{R_{\rm p} + R_*}{a}\,. \tag{11}$$

In almost all cases $R_{\rm p} \ll R_*$, so for planets at $\sim$AU radii the transit probability is $p \sim 10^{-3}$–10^{-2}. Transit searches must therefore observe large numbers of stars in order to detect planets, and are very strongly biased towards short-period orbits[5]. Note also that transits provide only orbital periods and planet radii; follow-up observations (usually RV, but sometimes transit-timing or other dynamical methods) are required to validate these detections and determine planet masses[6].

Ground-based transit surveys (primarily SuperWASP and HAT, and more recently "second generation" surveys like NGTS) have discovered hundreds of new planets, but are generally limited to >0.1% precision and have therefore primarily detected large ($\sim$Jupiter-size) planets in relatively short-period orbits. However, NASA's *Kepler* satellite, which originally operated from May 2009 until May 2013[7], revolutionised this field. To date *Kepler* has been responsible for over 2000

[5]By comparing Equations 8 and 11 we see that transit searches are more strongly biased towards small orbital separations than RV surveys, by a factor $a^{1/2}$.

[6]Note also that both RV and transit observations only measure the planet's properties relative to those of the host star. In many cases the absolute uncertainties in planetary masses and radii are dominated by the corresponding uncertainties in the properties of the host star.

[7]*Kepler*'s "prime mission" ended with the failure of a second reaction wheel in May 2013. From 2014–18 the satellite operated in a new mode, dubbed *K2*, which has slightly lower photometric precision than the original mission, but surveys a much larger area of the sky. *Kepler* finally ceased operations in late 2018.

confirmed exoplanet detections, and identified approximately 2500 additional candidate planets[8]. *Kepler* reached a precision of $\sim$10ppm, and its survey of over 100,000 stars is complete down to planets of approximately Earth radius for periods $\lesssim$1yr.

3 Summary of exoplanet observations

In the last decade years we have started to move from an era of simply detecting exoplanets, to one of characterising and studying them in detail. There is still a great deal to learn, but certain observational results and trends are now clear. The most important results (for our purposes – understanding planet formation) are as follows:

- Most, and perhaps all, stars host planets. Formally, RV surveys find that >50% of solar-type stars host at least one detectable planet with $P < 100$ days. If one cuts the data differently, we find that around F-, G- & K-type stars the frequency of gas-giant planets with $M_{\rm p} > 1{\rm M_{Jup}}$ and $a \leq 3$AU is 5–10%. Statistical studies from *Kepler* are limited to periods of $\lesssim$ 1yr, but suggest that the frequency of smaller planets ($\gtrsim$Earth-size) is >85%. All of these are lower limits to the total frequency, and will increase as we extend our knowledge to lower planet masses and larger orbital separations.

- Multiple planet systems are common. The selection biases here are subtle, but in the final data release from *Kepler* almost a quarter of detected systems had multiple planet candidates, with roughly half the total number of planet candidates found in multiple systems. (These numbers are again effectively lower limits, and seem certain to increase.)

- Unlike the Solar System planets, many exoplanets are in eccentric orbits. Giant planets at AU radii have a median eccentricity $\langle e \rangle \simeq 0.3$; some exoplanets have eccentricities > 0.9.

- The frequency of "hot Jupiters" (gas giant planets with $a \leq 0.1$AU) is approximately 1%.

- Giant planets at large separations are rare. Direct imaging surveys of nearby stars find that the frequency of 1–20${\rm M_{Jup}}$ planets with separations 20–200AU is $< 5\%$.

- The mass/size distribution of planets is relatively well-fit by a smooth power-law for giant planets (approximately $dN/dM_p \propto M_p^{-1}$), but turns over at lower masses/sizes and is approximately flat below 2–3${\rm R_\oplus}$.

- The radial distribution of giant planet orbits is fairly smooth for $a \lesssim$ 5–10AU: it resembles a power-law, increasing to larger a, and has few strong features at any particular values of a. The only statistically significant features in the distribution are a strong excess of giant planets in 3–5 day orbits, and possibly a weaker "pile-up" of $\sim$Jupiter-mass planets at 1–2AU.

- The frequency of giant planets increases very strongly with the metallicity of the host star: stars with $Z = 2Z_\odot$ are 5–10 times more likely to host giant planets than stars with $Z = 0.5Z_\odot$[9].

- This metallicity correlation does not hold for lower planet masses: the frequency of super-Earths and Neptunes is largely independent of Z.

[8] The majority of the *Kepler* target stars are too faint for spectroscopic follow-up, so most of these candidates will not be confirmed in the foreseeable future (if ever). However, the criteria adopted to define candidates are strict, and the false positive rate is estimated to be low ($\simeq$ 10%).

[9] There is some evidence that the pile-up of hot Jupiters in 3–5 day periods is only seen in high-metallicity stars; there also appears to be a correlation between host star metallicity and planet eccentricity.

- Compact systems, with multiple super-Earth- or Neptune-size planets in short-period (<50 day) orbits are very common.
- The observed mass-radius relation is relatively tight for gas-giant ($\gtrsim$0.1$M_{\rm Jup}$) and rocky ($\lesssim$2$M_\oplus$) planets, but shows very large scatter at intermediate masses[10].
- Some planets have orbits which are significantly inclined to the stellar rotation axis, and a few have even been found on retrograde orbits. High obliquities are much more common around hotter (more massive) stars than around solar and later-type stars.
- Planets form readily in binary systems, in both S-type (circumstellar) and P-type (circumbinary) orbits.

In addition, we are entering an era where we can characterise exoplanet properties in detail. We have taken spectra of exoplanetary atmospheres in transiting systems, and this is starting to become possible for directly imaged planets also. We are also detecting younger and younger planets, some of which are still embedded in debris or even protoplanetary discs. Future study of exoplanets in this manner will give us a much clearer idea of their structure and composition, and will provide many important clues as to how planets form.

4 Further Reading

In addition to the main list of references given on the course home-page, the following papers are particularly relevant to this lecture:

Wolszczan & Frail, *A planetary system around the millisecond pulsar PSR1257 + 12*, 1992, Nature, 355, 145.
Latham et al., *The unseen companion of HD114762 - A probable brown dwarf*, 1989, Nature, 339, 38.
Mayor & Queloz, *A Jupiter-mass companion to a solar-type star*, 1995, Nature, 378, 355.
Charbonneau et al., *Detection of Planetary Transits Across a Sun-like Star*, 2000, ApJ (Letters), 529, L45.
Kalas et al., *Optical Images of an Exosolar Planet 25 Light-Years from Earth*, 2008, Science, 322, 1345.
Marois et al., *Direct Imaging of Multiple Planets Orbiting the Star HR 8799*, 2008, Science, 322, 1348.
Udry & Santos, *Statistical Properties of Exoplanets*, 2007, ARA&A, 45, 397.
Batalha et al., *Planetary Candidates Observed by Kepler III: Analysis of the First 16 Months of Data*, 2013, ApJS, 204, 22.
Mullally et al., *Planetary Candidates Observed by Kepler VI: Planet Sample from Q1–Q16 (47 Months)*, 2015, ApJS, 217, 31.
Howard et al., *The Occurrence and Mass Distribution of Close-in Super-Earths, Neptunes, and Jupiters*, 2010, Science, 330, 653.
Mayor et al., *The HARPS search for southern extra-solar planets XXXIV: Occurrence, mass distribution and orbital properties of super-Earths and Neptune-mass planets*, `arXiv:1109.2497`.
Fischer & Valenti, *The Planet-Metallicity Correlation*, 2005, ApJ, 622, 1102.
Dawson & Murray-Clay, *Giant Planets Orbiting Metal-rich Stars Show Signatures of Planet-Planet Interactions*, 2013, ApJ (Letters), 767, L24.
Petigura et al., *A Plateau in the Planet Population below Twice the Size of Earth*, 2013, ApJ, 770, 69.

[10] Note, however, that measurement errors on both $M_{\rm p}$ and $R_{\rm p}$ are typically $\gtrsim$10-20%, and this translates to typical uncertainties of $\gtrsim$50% in the mean density of transiting planets. As mentioned above, the uncertainties in the mass and radius of the host star are usually the limiting factor when we measure planetary properties at high precision.