Main results of exoplanets studies

Statistical properties
Mostly based on the results obtained with the Doppler and Transit methods which provide the largest statistics so far

Updated results can be found at: exoplanets.org e exoplanet.eu

Understanding observational biases is fundamental to interpret the observed statistical properties
Number of detected exoplanets versus apparent magnitude of the host star

Brighter stars provide more signal-to-noise ratio but there is a small number of very bright stars

Statistics of orbital parameters

- One of the main results of exoplanets studies is the great variety of observed orbital parameters
- Such variety is not found in the Solar System
- The statistics of orbital periods (i.e., semimajor axis) and eccentricities have the largest amount of data and are the best investigated

Exoplanet statistical properties

- Main types of statistical properties that can be investigated
  - properties of planetary orbits
    Orbital periods, semimajor axis, eccentricity, orbital inclination
  - planetary properties
    Masses and radii
    with the Doppler and transit methods, respectively
  - properties of the host stars
    Metallicities, chemical abundance patterns

Distribution of orbital periods

- The distribution peaks at short orbital periods
  - The general trend is the result of several types of selection effects
    The limited temporal baseline of the observations tends to favour short orbital periods
    For a given planetary mass, a planet closer to the star (i.e. with shorter period) generates a stronger reflex motion of the host star
    A planet closer to the star has a higher geometric probability of detection with the transit method
Distribution of orbital periods

- Evidence for the existence of a peak at $P \approx 3$ days
  - The decrease of frequency at shorter periods cannot be attributed to selection effects
  - The existence of such peak was unexpected from a theoretical point of view
  - Provides important constraints on models of planetary formation and evolution
  - In particular, suggests the existence of a mechanism that breaks the migration of planets towards the central star

Distribution of eccentricities

- The distribution shows the existence of planets in highly eccentric orbits
  - Virtually the complete possible interval of eccentricities, between 0 and 1, is covered
  - The vast majority of eccentricities is higher than in Solar System planets
- Low eccentricity orbits are more frequent
  - The shape of the distribution is affected by observational selection effects and can vary according to the type of observational method adopted to collect the sample

Minimum mass of exoplanets

Statistics of planets discovered with the Doppler method

The detection limit is becoming more stringent in the course of the years
Minimum mass of exoplanets
Statistics of planets discovered with the Doppler method

“Saturns”
\[ M \sim 0.3 \, M_J \]

“Neptuns”
\[ M \sim 0.05 \, M_J \]

“Super-Earths”
\[ M \sim 0.015 \, M_J \]
\[ M_p \sim 10 \, M_{\text{Earth}} \]

Masses intermediate between the Earth’s and Neptune’s masses do not exist in the Solar System

Terrestrial
\[ M \sim 0.003 \, M_J \]

Planetary mass versus semimajor axis

• Results from the Doppler method
  – Most detected planets lie within a few AU from the central star

• Discovered “hot-Jupiters”, i.e. giant planets within \( \leq 1 \, \text{AU} \) from the stars
  – Unexpected result from our previous understanding of the Solar System architecture

Orbital parameters and planetary mass

– Eccentricity \( e \) versus semimajor axis \( a \); the symbol sizes are proportional to the minimum mass \( (M \sin i) \)
– The plot shows the great dispersion of the orbital parameters \((a, e)\) and planetary masses
– In the Solar System, the eccentricities are usually small and other regions of the parameter space are not covered

Planetary mass versus semimajor axis

• At large distances from the star, the detected planets are quite massive
  – Selection effect: at large semimajor axis, only massive planets have the capability to generate a significant reflex motion of the star
  – Physical effect: most massive planets form at larger distances from the central star, where the longer orbits provide more material for the planet to form by accretion

Mercury’s semimajor axis
Planetary mass versus semimajor axis
Comparison of results obtained with the different observational methods
One of the future aims is to cast light on the population at the bottom-right of this figure, typical of Solar System planets

Radii versus period: Kepler data

Exoplanets radii versus semimajor axis

- Sample of exoplanets obtained with the transit method, not corrected for selection bias
- The results are biased because the geometric probability scales as $R_*/a$ and the transit depth scales as $(R_p/R_*)^2$
- However, the "sub-jovian" desert seems to be real
- Its interpretation is complex and requires invoking planetary migration and disruption (Matsakos & Koenig 2016)

Exoplanets radii versus semimajor axis

- A large number of terrestrial-size planets are found, despite the difficulty of detecting small planets
- Terrestrial-size planets are still difficult to detect at large values of semimajor axis
Occurrence rates

- A general result provided by exoplanet surveys is that planetary systems are quite common around stars.
- The high occurrence rate favours scenarios in which the process of planetary formation is closely related to the process of stellar formation.
- In absence of exoplanet observations, one could invoke alternative scenarios, in which planets arise from events that are distinct from star formation.
- An example was the tidal theory, in which planets condense from material stripped from a star during a chance encounter with another star.
- This type of event is extremely unlikely and would yield a very small fraction of planetary systems, contrary to what we now observe.

Occurrence rates around FGK stars

<table>
<thead>
<tr>
<th>Study</th>
<th>Technique</th>
<th>Period range</th>
<th>Mass range</th>
<th>Occurrence [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wright et al. (2012)</td>
<td>Doppler</td>
<td>&lt;30 days</td>
<td>&gt;10M_⊙</td>
<td>1.20 ± 0.38</td>
</tr>
<tr>
<td>Mayor et al. (2011)</td>
<td>Doppler</td>
<td>&lt;30 days</td>
<td>&gt;10M_⊙</td>
<td>0.89 ± 0.36</td>
</tr>
<tr>
<td>Cumming et al. (2008)</td>
<td>Doppler</td>
<td>&lt;5 years</td>
<td>&gt;100M_⊙</td>
<td>8.5 ± 1.3</td>
</tr>
<tr>
<td>Howard et al. (2010)</td>
<td>Doppler</td>
<td>&lt;100 days</td>
<td>&gt;100M_⊙</td>
<td>2.4 ± 0.7</td>
</tr>
<tr>
<td>Mayor et al. (2011)</td>
<td>Doppler</td>
<td>&lt;50 days</td>
<td>5-100M_⊙</td>
<td>11.6 ± 4.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;50 days</td>
<td>10-50M_⊙</td>
<td>13.1 ± 2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;50 days</td>
<td>&gt;50M_⊙</td>
<td>11.9 ± 1.7</td>
</tr>
<tr>
<td>Pratko et al. (2013)</td>
<td>Transit</td>
<td>&lt;30 days</td>
<td>6-22R_⊙</td>
<td>0.8 ± 0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;5 days</td>
<td>1.25-20R_⊙</td>
<td>20.3 ± 1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;5 days</td>
<td>2-4R_⊙</td>
<td>19.9 ± 1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;5 days</td>
<td>1.25-22R_⊙</td>
<td>52.3 ± 4.2</td>
</tr>
<tr>
<td>Perreira et al. (2013)</td>
<td>Transit</td>
<td>5-100 days</td>
<td>1-2R_⊙</td>
<td>26 ± 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-100 days</td>
<td>8-16R_⊙</td>
<td>1.6 ± 0.5</td>
</tr>
</tbody>
</table>

Occurrence rates

- The study of occurrence rates corrected for observational selection effects provides powerful constraints to models of planetary formation.
- The occurrence rate is the mean number of planets per star having properties within a specified range.
- In practice, the planet properties are chosen among those measurable with a given observational technique.
- For instance, for a survey performed with the Doppler method one can define the occurrence rate as the mean number of planets per star having masses and orbital periods within a specified range.

\[
\frac{dN}{d\ln P \, d\ln M}
\]

- To cope with selection effects, one limits the range of planetary quantities according to the observational limits.
- As an example, \( M_p > 10 \, M_\oplus \) and \( P < 1 \, \text{yr} \).

Trends of occurrence rates

- Within the specified observational limits, occurrence rates can be modelled with simple analytical functions.
- For instance, the occurrence rate derived from Doppler surveys of FGK stars, \( M_p > 100 \, M_\oplus \) and \( P < 5.5 \, \text{yr} \), can be modelled as

\[
\frac{dN}{d\ln P \, d\ln M_p} \propto M_p^\alpha \, P^\beta
\]

- With \( \alpha = -0.31 \pm 0.20 \) and \( \beta = 0.26 \pm 0.10 \) (Cumming et al. 2008).
- This result suggests that the planet frequency increases with decreasing mass and increasing orbital period.
- The results cannot be extrapolated outside the observational limits.
Distribution of planetary masses

- $M \sin i$ distribution obtained with the Doppler method
  - The distribution increases towards values of low mass
  - Despite the selection effect that favours the detection of high mass planets
  - Whether this trend extends to the terrestrial mass regime needs to be confirmed with a larger sample of Earth-mass planets

Occurrence rates of Earth-like planets

- The occurrence rate of Earth-like planets is usually calculated taking into account the planet mass (or size), and the insolation (rather than the orbital period or semimajor axis)
  - The insolation is a key parameter that governs the planet surface temperature and habitability
  \[ S = \frac{L_\star}{4\pi a^2} \]
  - The motivation for calculating the occurrence rate of Earth-size planets according to their level of insolation is astrobiological
  - The choice of the interval of insolations is dictated by the definition of circumstellar habitable zone that we will discuss in a subsequent lesson

Distribution of planetary radii

- Once corrected for selection effects, also the distribution of radii indicates that small-size planets are more frequent than large planets

Occurrence rates of Earth-like planets

<table>
<thead>
<tr>
<th>Type of star</th>
<th>Type of planet</th>
<th>Approximate HZ boundary$^1$ [ES/Sp]$^2$</th>
<th>Occurrence rate [%]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>0.3–0.5 $M_\odot$</td>
<td>0.75–2.0</td>
<td>41$^{+21}_{-10}$</td>
<td>23</td>
</tr>
<tr>
<td>FGK</td>
<td>0.8–2.0 $R_\odot$</td>
<td>0.3–1.8</td>
<td>24$^{+5}_{-2}$</td>
<td>11</td>
</tr>
<tr>
<td>FGK</td>
<td>0.5–2.0 $R_\odot$</td>
<td>0.8–1.8</td>
<td>14 ± 4</td>
<td>18</td>
</tr>
<tr>
<td>M</td>
<td>0.5–1.4 $R_\odot$</td>
<td>0.46–1.0</td>
<td>13$^{+2}_{-1}$</td>
<td>23</td>
</tr>
<tr>
<td>FGK</td>
<td>1–2 $R_\odot$</td>
<td>0.25–4.0</td>
<td>11 ± 4</td>
<td>15</td>
</tr>
<tr>
<td>FGK</td>
<td>1–2 $R_\odot$</td>
<td>0.25–4.0</td>
<td>11 ± 4</td>
<td>15</td>
</tr>
<tr>
<td>FGK</td>
<td>1–2 $R_\odot$</td>
<td>0.25–4.0</td>
<td>11 ± 4</td>
<td>15</td>
</tr>
<tr>
<td>G</td>
<td>0.6–1.7 $R_\odot$</td>
<td>0.35–1.5</td>
<td>13$^{+2}_{-1}$</td>
<td>23</td>
</tr>
</tbody>
</table>

$^1$In many cases the actual habitable zone (HZ) definitions used by the authors were more complex, please refer to the original papers for details.

$^2$Refers to the incident flux of sunlight on the planet, and $L_\star$ to the Earth's insolation. All these works are based on Kepler data except Beich et al. (2013), which is based on the HARPS Doppler survey, and Schlaufman (2014), which is based on both Kepler and the Keck Doppler survey.

$^3$The result is much lower than the others because the author also required the Earth-sized planet to have a long period giant planet companion.