Exoplanets characterization

- Study of the physical properties of individual planets
  - Direct imaging can provide experimental data useful to characterize individual planets
  - In general, the best way to constrain the properties of individual exoplanets is to combine different observational techniques
  - From this combination of experimental data, with the aid of modelization, we can derive information on
    - Planetary interiors
    - Planetary atmospheres
    - Planetary energy budget

Combination of different observational methods

- Doppler + transit methods
  - Combines the mass obtained from the Doppler method with the radius obtained with the transit method
  - The degeneration of the orbital inclination $\sin i$ is solved
    - Method already applied to a large number of cases

- Doppler + astrometric methods
  - Given the minimum mass $M \sin i$ from the Doppler method, one can in principle estimate $\sin i$ with the astrometric method; in this way one can obtain the mass, rather than the minimum mass
    - Currently limited due to the difficulty of astrometric observations

Estimate of planetary masses from Transit Timing Variations

Technique that can be applied to multiple planetary systems discovered with the transit method

In a planetary system with many planets in nearby orbits, gravitational perturbations will induce small variations in the timing of the transits
  - From a detailed analysis of the transit timings it is possible to deduce the mass of the planets, even without radial velocity observations

Examples:
  - Kepler-11 (Lissauer et al. 2011)
  - Trappist 1 (Gillon et al. 2017)
Planets with measurements of masses and radii

- From mass and radius measurement we obtain
  
  - **mean density** \( \rho \sim M/R^3 \)
  
  Casts light on the internal structure/composition of the planet

- **surface gravity** \( g \sim M/R^2 \)
  
  Important for the modelization of the atmosphere and climate

- **escape velocity** \( v_e \sim (M/R)^{1/2} \)
  
  Indicates the capacity for the planet to maintain an atmosphere

By comparing masses and radii with curves of equal mean density one can cast light on the bulk composition

Green curves: lines of uncorrected constant mean density

Most exoplanets discovered so far are gaseous (\( \rho < 1 \text{ g cm}^{-3} \)), but we are starting to discover rocky ones (\( \rho > 3 \text{ g cm}^{-3} \))

For low-mass planets, the radius increases with mass faster than \( R \sim (M/\rho)^{1/3} \)

i.e., faster than expected for the case of constant mean density

- The fast rise of the radius with mass is interpreted as an indication that during the process of planetary formation the planets initially accrete dense (refractory) material and then low-density (volatile) material

- As a result, the mean density decreases as the accumulated mass (or size) increases
**Mass versus radius: theoretical relations for planets of low mass**

Mass versus radius for planets composed of H\textsubscript{2}O ice, rock (Mg\textsubscript{2}SiO\textsubscript{4}), and iron

Thin curves are calculated for different values of fractional composition and different temperatures

From Fortney et al. 2007)

**Mean density versus radius and insolation**

Sample of planets with $M < 10$ Earth masses and reliable measurements of $M$ and $R$

- The uncorrected mean density decreases with increasing planet size (dashed line)
- The level of insolation tends to decrease with decreasing density
  - This implies that the insolation plays an important role in the process of planetary accretion
  - Possible interpretation: at high level of insolation only dense, refractory material is accumulated

**Mean density versus radius and insolation**

Sample of planets with $M < 10$ Earth masses and reliable measurements of $M$ and $R$

- Solar System planets do not follow the experimental trend observed in exoplanets
- At a given density and radius, their level of insolation is much lower
- Current samples of exoplanets are not representative of Solar System conditions, even when we consider planets with similar radii and densities
- This situation will change when data of terrestrial-type planets with lower level of insolation will be accumulated

Mass-radius plots showing selected rocky planets
Curves show models with different compositions
Planets are color coded according to their incident stellar flux
The large variety of exoplanet properties suggests that planets with masses in the range between Earths and super-Earths may have bulk composition dominated by volatiles such as H\(_2\)O ice, rather than rocky material. Such objects, called ocean planets, could form at large orbital distances, beyond the snow line.

In the range 1-10 Earth masses they are not expected to accumulate a large H/He envelope (at variance with icy/gaseous giants of the Solar System). A fraction of such planets could have migrated inwards, in a region where water can be in liquid phase, leading to the existence of “water worlds.”

Candidate ocean planet:
example: GJ 1214 b (d=13 pc, M=6.6M\(_\oplus\), R=2.7R\(_\oplus\), \(\rho=1.9\) g cm\(^{-3}\))

Exoplanet characterization: observations of radiation emitted by the planet

- The faint radiation emitted by planets has two contributions
  - Intrinsic thermal emission
    The study of the thermal emission is carried out in the infrared band
    Provides direct information on the planet surface temperature and the atmospheric properties of the outer layers
  - Reflected stellar radiation
    The study of the stellar light reflected by the planet is carried out in the visible band
    Provides information on the albedo properties of the outer layers

Exoplanet characterization: observations of planet radiation

- Methods to measure the exoplanet radiation
  - Direct imaging
    If the image of the planet is solved, the thermal emission can be directly measured
    In this case, however, the planet-star separation will be quite high and, as a result, the stellar light reflected by the planet cannot be measured
  - Secondary transits
    By studying the light curve at the epoch in which the planet is hidden by the star ("secondary transit")
Effective temperatures derived from the thermal emission of exoplanets
by means of direct imaging
Masses can be estimated from models of planet evolution

Infrared luminosities obtained from direct imaging require a modelization of the planet evolution
- Evolution of radii, effective temperature and luminosity for different values of planetary mass in the Jupiter’s range
- Dotted lines: models of adiabatic formation in which the planet retains most of the accretion energy
- Solid lines: models with standard core accretion paradigm
- In either case, planets are significantly easier to detect at young ages (from Marley et al. 2007)

Secondary transits
Secondary transit (or secondary eclipse)
- Transit of the planet behind the star (the planet is eclipsed by the star)
  With a proper geometric configuration of the orbits

In the Rayleigh-Jeans limit, valid at long wavelengths, the emission scales linearly with $T$, and the depth of the secondary eclipse is given by

$$\Delta F \approx \frac{T_p}{T_*} \left( \frac{R_p}{R_*} \right)^2$$
Secondary transits

Example:

Infrared light curve of HD 189733A and b (K1-K2 star at 19 pc, \( M_p = 1.15 \, M_J \), \( a = 0.03 \, \text{AU} \))

The first dip (left) is the transit and the second dip the secondary eclipse

Bottom panel: a zoom of the top panel

Surface temperature distribution of tidally-locked Hot Jupiters

Example:

- HD 189733b observed in the IR with Spitzer-IRAC (Knutson et al. 2007)
- The longitudinal variation of the surface temperature is not very high, in spite of the tidal locking
- The relatively small temperature variation suggests the existence of an efficient mechanism of heat diffusion along the planet surface

Surface temperature distribution of tidally-locked Hot Jupiters

- For transiting Hot Jupiters the light curves of primary and secondary transits can be combined to derive information on the light emitted by the planet at different orbital phases
- Assuming that the planet is tidally locked, the orbital phase can be converted in phase of planetary rotation
- In this way it is possible to reconstruct the surface emissivity as a function of planet longitude