Indirect methods of exoplanet detection: luminosity variations of the host star

- Variations of stellar luminosity induced by the presence of an orbiting planet or planetary system
  - A light curve is built up using the variations of stellar luminosity
  - These indirect methods require a specific geometrical configuration

- Methods
  - Gravitational microlensing
    From the light curve of a background star physically unrelated with the planet/star system
  - Transit method
    From the light curve of the planet’s host star

Gravitational microlensing

May take place when a star-planet system crosses the visual of a background star, as a result of the relative proper motion

During the crossing, the intervening star-planet system acts as a gravitational lens for the background star

- The background star shows a temporal rise of its luminosity as a result of the gravitational lensing effect

For a suitable geometric configuration, the planet around the intervening star can intensify the lensing effect during its orbital motion

- In this case, the light curve of the background star shows an additional, transient emission peak

Gravitational microlensing

Predicted by General Relativity

Einstein ring radius

\[ R_{E} = \theta_{E} D_{L} = \frac{4GM(D_{S} - D_{L})}{c^{2}D_{S}} \]

\(^{\text{Bennet (2009)}}\)

The gravitational lensing effect is maximum when \( D_{L} \approx 0.5 D_{S} \)
Gravitational microlensing

• Measurable quantities
  – Planet/star mass ratio, $q = M_p/M_*$
  – Planet-star distance, $d$, in units of the Einstein radius, $R_E$

Given the mass of the lensing star and the geometric configuration of the lens, one can determine the mass and radius of the planet.

The spectrum of the intervening host star cannot be distinguished from that of the background star.

The mass of the host star is estimated from the lens parameters.

Gravitational microlensing

• The probability of finding a system with proper geometric configuration increases with the square of the density of the background stars.
  – Microlensing effects are searched for in crowded stellar fields.
  – Images of the same field taken at different epochs are regularly compared to each other.
  – The continuous coverage of a given field of the sky requires an international collaboration between observatories located at different geographical longitudes.

• Example of crowded field used to search for microlensing effects.
  – The Galactic Bulge, located in the central region of the Milky Way.
  – Collaboration among observatories of the Southern hemisphere.

OGLE (Optical Gravitational Lensing Experiment)

http://ogle.astrouw.edu.pl

Originally planned to discover microlensing effects due to the presence of baryonic dark matter along the line of sight.

Gravitational microlensing

• Advantages
  – Able to detect small-mass planets of terrestrial type.
  – Multiple planetary systems can be found in a single event.
  – In principle, one could also detect free-floating planets (i.e. planets that do not orbit a star).
  – Effective to detect distant planetary systems.

  The gravitational lensing effect is maximum when the lensing star lies at about half the distance between the observer and the background star.

Since the stars of the Galactic Bulge lie at several kiloparsecs, planetary systems can be found at distances of some kiloparsecs.

• Disadvantages
  – Unique event, impossible to predict.
  – The planetary system cannot be investigated with follow-up observations.
  – The lensing, host star is not observable.
  – Orbital parameters are poorly determined (essentially the semimajor axis).

Example of gravitational microlensing

OGLE-2005-BLG-390Lb (Beaulieu et al. 2006)

Figure 1: The observed light curve of the OGLE-2005-BLG-390Lb microlensing event and best fit model plotted as a function of time. The data set consists of 650 data points from PLANET Danish (ESO La Silla, red points), PLANET Perth (blue). PLANET Canopus (Hobart, cyan), RoboNet Faulkes North (Hawaii, green), OGLE (Las Campanas, black), MOA (Mt John Observatory, brown).
Example of planetary system discovered with the microlensing method
OGLE-2012-BLG-0026Lb,c (Han et al. 2013)
Two giant planets located beyond the "snow-line"; Distance from Earth: ~ 4.1 kpc

Gravitational microlensing method
comparison with other methods

So far, discovered about 30 planets with a wide range of masses

Indirect methods of exoplanet detection:
luminosity variations of the host star

The transit method

Transit method

If the line of sight is aligned with the orbital plane, the planet will produce a minimum in the light curve during its transit in front of the stellar disk. The stellar light curve will show a characteristic periodic behaviour.

Geometric configuration: $i \approx 90^\circ$
**Transit method**

- **The light curve**
  - The exact shape of the light curve is complex since it depends on stellar, orbital, and planetary parameters, as well as on the geometric configuration of the observation, including the impact parameter.
  - Impact parameter: projected (angular) distance between the planet center and the center of the stellar disk:
    \[ b = \frac{a}{R_*} \cos i \]

- **Effect of the limb darkening on the light curve**
  - The limb darkening refers to the drop of intensity of a stellar image moving from the center to the limb of the stellar disk.
  - This darkening results from the combined effect of optical depth with the decreasing star density and temperature with radius.
  - The limb darkening should be taken into account to model the light curve.

**Transit method**

- **Central depth of the light profile**
  - Neglecting the flux emitted by the planet and the “limb darkening” of the stellar disk, the depth of the profile is:
    \[ \Delta F_r = \frac{F - F_{tr}}{F} = \left( \frac{R_p}{R_*} \right)^2 \]
    
    - \( F \): stellar flux outside the transit
    - \( F_{tr} \): stellar flux during the transit (minimum of the light curve)
    - \( R_p \): planet radius
    - \( R_* \): stellar radius

**Transit method**

- **Magnitude of the effect**
  - Expected central depths for planets transiting a solar-type star (\( R_* = R_\odot \))
    - For a giant planet, \( R_p = R_J \rightarrow \Delta F_r = 1\% \)
    - For an Earth-like planet, \( R_p = R_{\text{Earth}} \rightarrow \Delta F_r = 0.01\% \)
  - Requires a high photometric accuracy.
Transit method

- Other parameters that can be measured from the light curve profile
  - Total duration of the transit interval between the first and fourth contact
  - Duration of the entrance interval between the first and second contact

Transit method

- Transit duration
  - The total transit duration, \( t_T \), is a function of the following orbital, stellar, and planetary parameters:
    \[ t_T = t_T(P, \frac{R_p}{R_*}, \frac{a}{R_*}, i) \]
  - Setting \( i=90^\circ \) and \( b=0 \), and using a relation between stellar masses and radius, the duration of the transit for a circular orbit is numerically
    \[ t_T \approx 13 \left( \frac{M_*}{M_\odot} \right)^{-1/2} \left( \frac{a}{1 \text{AU}} \right)^{1/2} \left( \frac{R_*}{R_\odot} \right) \text{ hours} \]
  - As an example, this gives a total transit interval of about 25 h for a Jupiter-type orbit and 13 h for an Earth-type

Transit method

- From observable quantities to orbital/planetary parameters
  - The time interval between subsequent transits provides the orbital period \( P \)
  - The minimum of the light curve yields \( R_p/R_* \)
  - From an estimate of the stellar radius \( R_* \), one derives \( R_p \)
  - \( R_* \) can be derived, as usual, from the classification of the star, but can also be inferred from a parametrization of the light curve profile
  - The exact shape of the light curve at the entrance of and during the transit can be used to constrain \( R_*, M_*, a, R_p \) and \( \cos i \)

Transit method

- Geometric probability
  - The geometric probability of detecting a planet with the transit method is proportional to \( \frac{R_*}{a} \)
    \[ R_*: \text{stellar radius; } a: \text{orbital semi-major axis} \]
  - Typical value of the geometric probability:
    \[ P_{\text{geom}} \sim 0.0045 \left( \frac{1 \text{AU}}{a} \right) \left( \frac{R_*}{R_\odot} \right) \]
    Charbonneau et al. (2007)
  - The probability of observing a transit at a given moment also depends on the duration of the transit phase
    \[ t_T \approx 13 \left( \frac{M_*}{M_\odot} \right)^{-1/2} \left( \frac{a}{1 \text{AU}} \right)^{1/2} \left( \frac{R_*}{R_\odot} \right) \text{ hours} \]
Transit method

• Selection effects
  – The transit signal increases with \((R_p/R_*)^2\)
    Easier to find large planets orbiting small stars
  – Observations biased by the geometrical probability \(p_{geom} \sim R_*/a\)
    Easier to find planets with small semi-major axis (short periods)
    Extremely difficult to find planets at distances larger di 5 - 10 AU

The selection effect of small semi-major axis reinforces the effect due
to the temporal baseline of the observations, which favours detections
of planets with short orbital periods

Relatively easy to find giant planets close to the host star
as an example, "hot-Jupiters"

Transit method

• Need for large surveys
  – To cope with the low geometrical probability, it is necessary to
    monitor the light curves of a large number of stars (>> 10^3)

• Need for continuous monitoring
  – A long term, continuous monitoring is required in order not to miss
    the transit event

Ground based observations require international collaborations
between observatories located at different geographical
longitudes

The advantage of ground-based surveys is the possibility of
covering the whole sky

Example: WASP (Wide Angle Search for Planets)

The continuous temporal coverage is more effectively performed
from space, but on more limited fields of the sky

Examples: satellites CoRot and Kepler

Kepler mission

http://kepler.nasa.gov

• The photometer on board of the Kepler
  satellite was designed to detect the transit of
  a terrestrial planet in front of a solar-type
  star with magnitude V=12 at 4 o level in 6.5
  hours of integration

• The mission was planned to continuously
cover a field with 10^5 main sequence stars
  up to magnitude 14 during 4 years

• Results (2015)
  – 3300 candidate planets
  – about 1000 confirmed planets

• Updated tables of the orbital/planetary
  parameters
  http://kepler.nasa.gov/Mission/discoveries/

Transit method: false positives

• Problem of the false positive detections
  – due to the presence of eclipsing binaries that happen to lie in the
    background, in the same line of sight of the star that hosts the planet

• Follow-up programs to cope with the false positives
  – Different types of methods are used to confirm the results obtained
    from the light curves

• Search for stellar binaries
  – With adaptive optics
    If an eclipsing binary is found in the field, it may create a false positive
detection; in the worst scenario, the eclipsing binary could be
perfectly aligned with the star that hosts the planet
  – With the spectroscopic method
    Eclipsing binaries can be discovered with the analysis of high
    resolution spectra, where they produce a characteristic splitting of
    the stellar lines, which varies according to the binary orbital period
Transit method: false positives

- Follow-up programs to cope with the problem of false positives and confirm the planet detection

- Doppler method
  - Requires a series of high resolution spectra covering at least one orbital period
  - It is the safest method since it also provides the planet’s mass, confirming the planetary nature of the object that causes the minimum of the light curve
  - However, the star should be sufficiently brilliant to perform high resolution spectroscopy (problem for Kepler targets)

Transit method: multiple planetary systems

Multiple planetary systems can be detected if the planetary system is coplanar

- Procedure
  - minima with different, regular periodicity are searched for in the light curve

- Limitation
  - Planets of the same system, but different orbital inclinations, escape detection

- Advantages of multiple planetary systems
  - if multiple transits are discovered, the probability of false positives due background binary stars become negligible
  - the detected minima can be safely attributed to planetary objects with no need of follow-up observations

Transit method comparison with other methods

Spans a very broad ranges of planetary masses, but the number of detected exoplanets decreases significantly with increasing semi-major axis