Exoplanets
Microlensing and Transit methods

Planets and Astrobiology (2019-2020)
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Indirect methods of exoplanet detection: luminosity variations of the host star

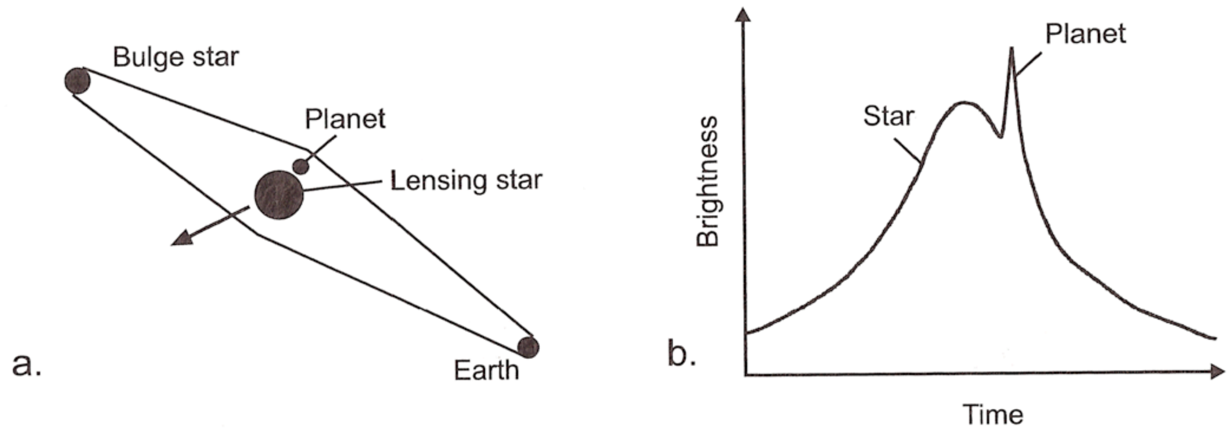
- Variations of stellar luminosity induced by the presence of an orbiting planet or planetary system
  - A light curve is built up using the variations of stellar luminosity
  - These indirect methods require a specific geometrical configuration

- 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

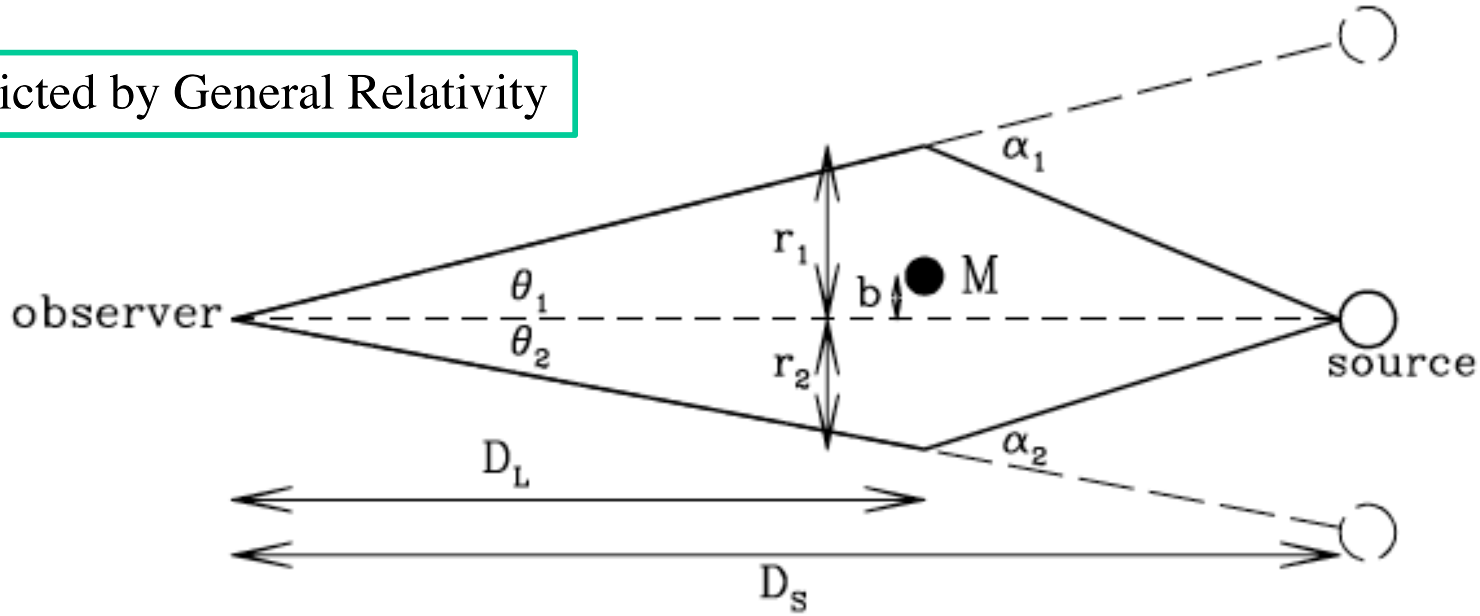


Fig. 1.1. The geometry of gravitational lens of mass, M, that is offset by a distance, b, from the line of sight to the source. The observer sees two images that are offset by angles, θ_1 and θ_2 from the line of sight to the source star.

Einstein ring radius

$$R_E \equiv \theta_E D_L \equiv \sqrt{\frac{4GM\, D_L(D_S - D_L)}{c^2\, D_S}}$$

Bennet (2009)

The gravitational lensing effect is maximum when $D_L \sim 0.5\ D_S$

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 present 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)

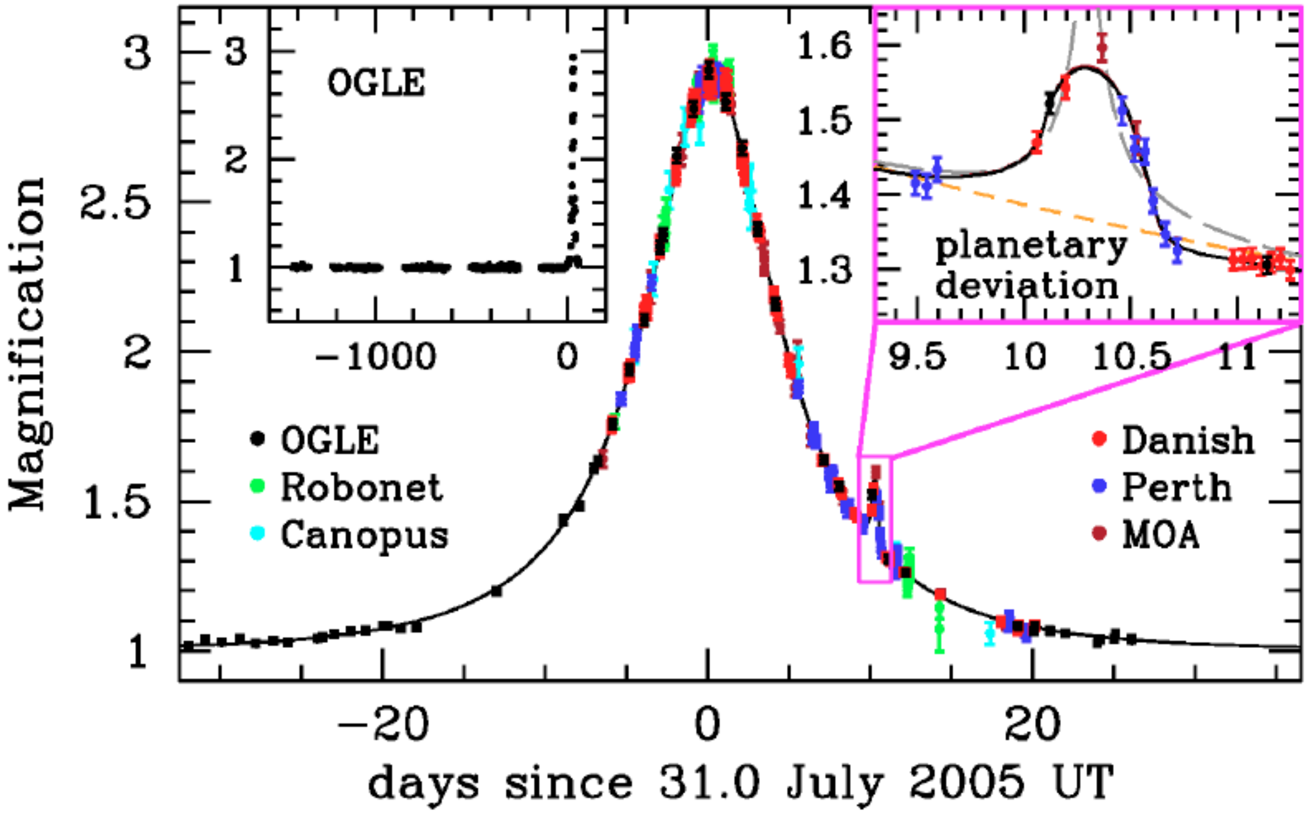
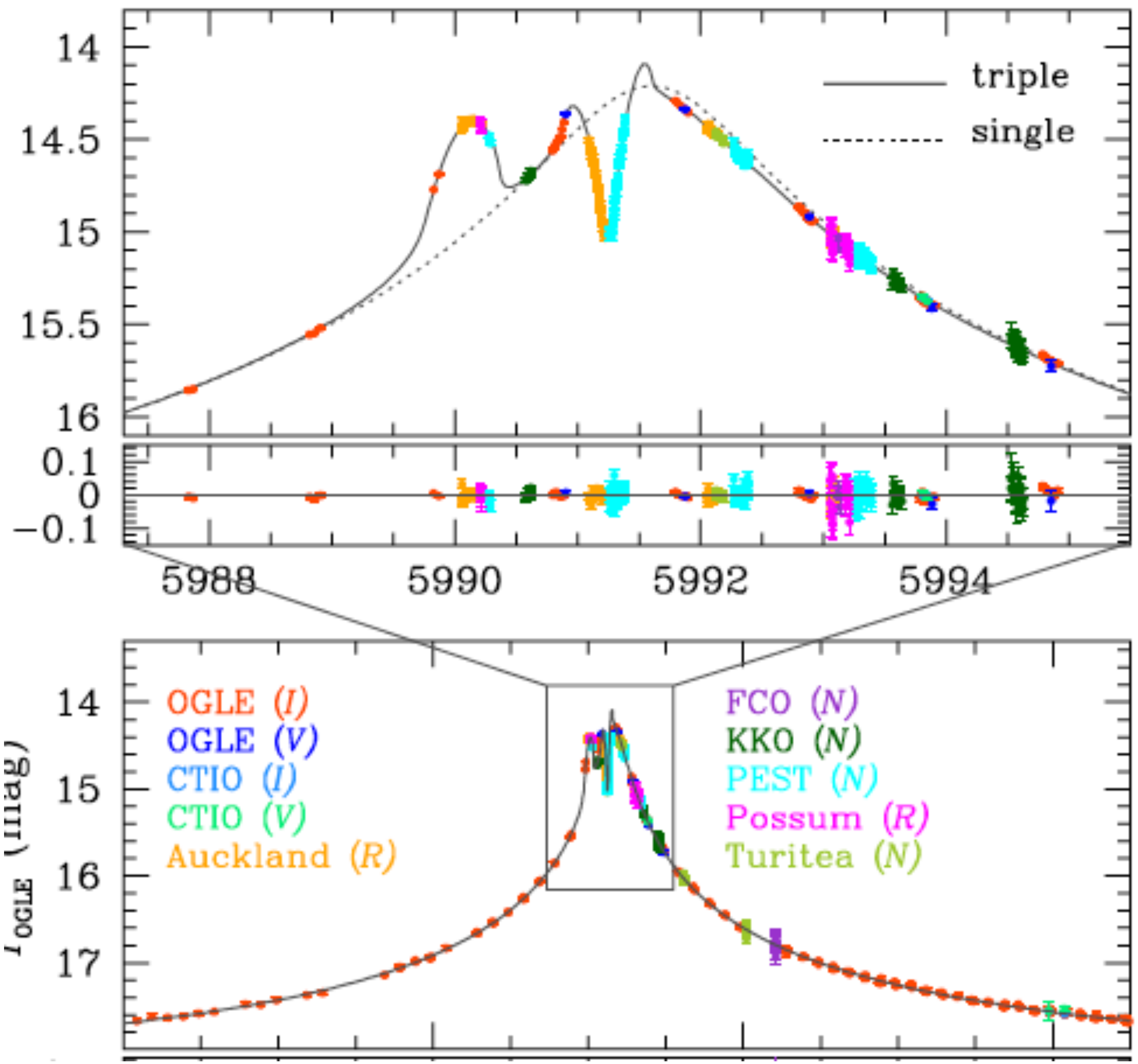


Figure 1 : The observed light curve of the OGLE-2005-BLG-390 microlensing event and best fit model plotted as a function of time. The data set consists of 650 data points from PLANET Danish (ESO La Silla, red points), PLANET Perth (blue), PLANET Canopus (Hobart, cyan), RoboNet Faulkes North (Hawaii, green), OGLE (Las Campanas, black), MOA (Mt John Observatory, brown).

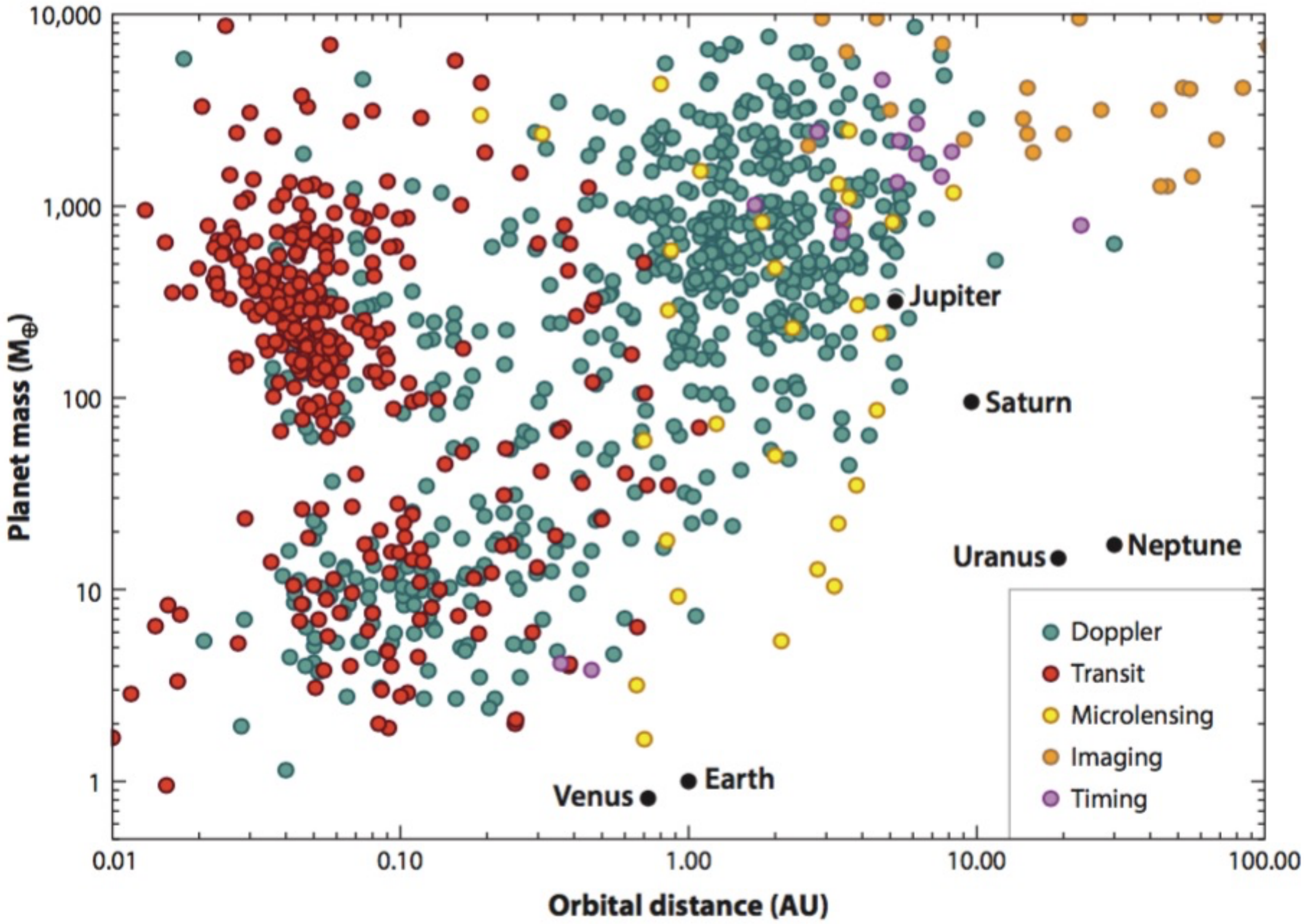
Example of planetary system discovered with the microlensing method
OGLE-2012-BLG-0026Lb,c (Han et al. 2013)
Two giant planets located beyond the “snow-line”; Distance from Earth: ~ 4.1 kpc



Gravitational microlensing method

comparison with other methods

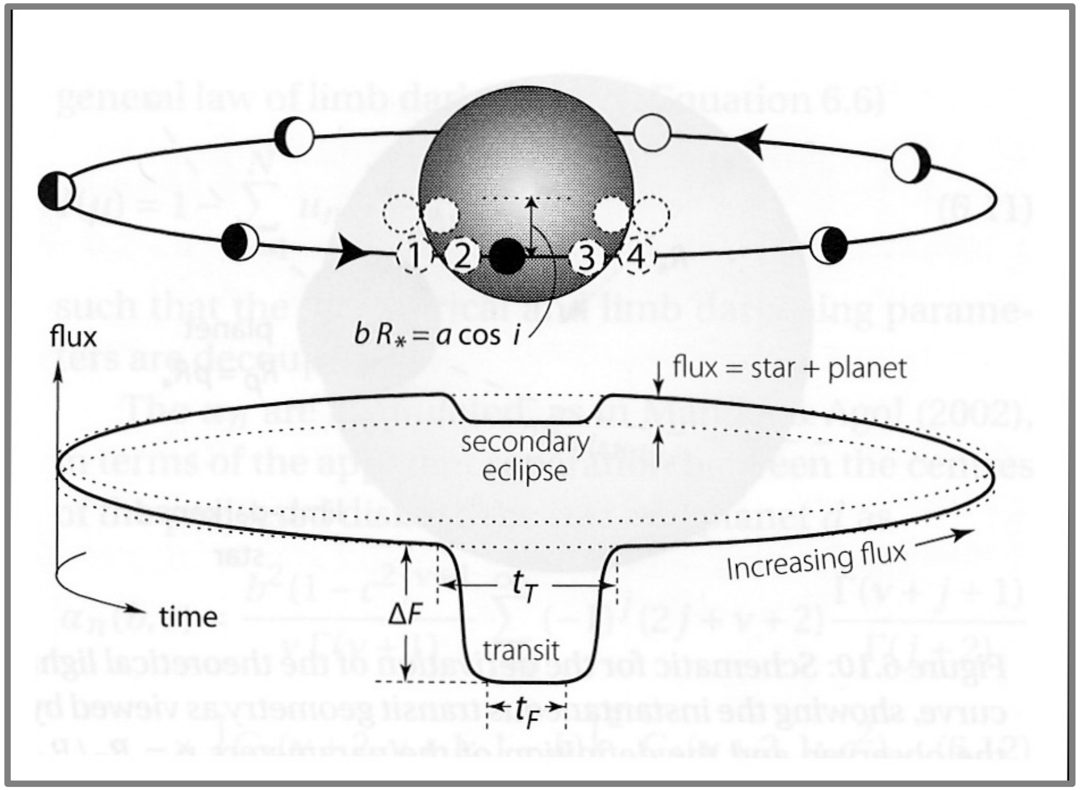
At present time (April 2018), discovered 71 planets (3 multiple planet systems) with a wide range of masses



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

The transit method

Transit method



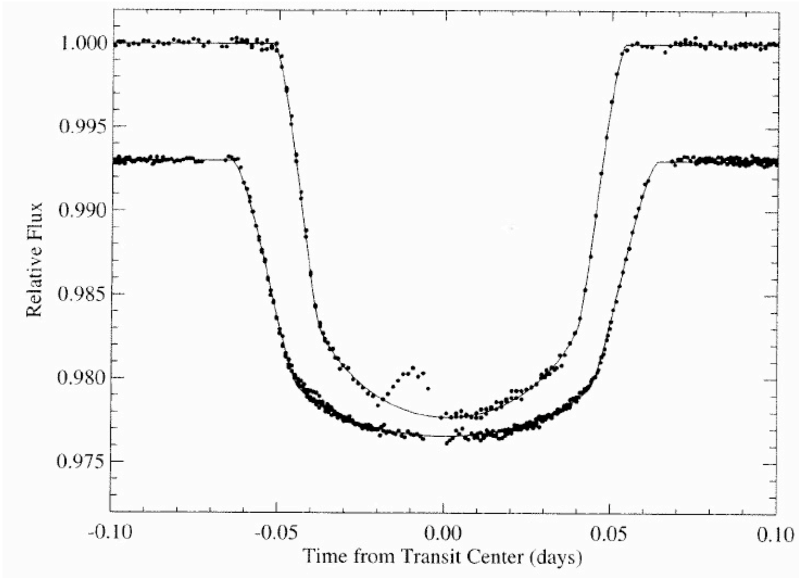
If the line of sight is aligned with the orbital plane, the planet will produce a minimum in the light curve during its transit in front of the stellar disk

The stellar light curve will show a characteristic periodic behaviour

Geometric configuration: $\boldsymbol{i} \approx 90^{o}$

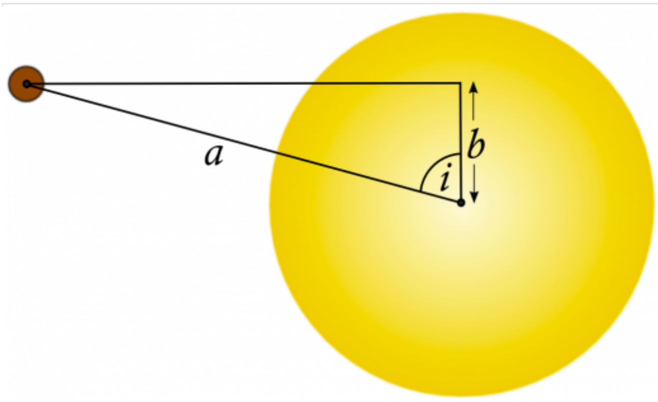
Transit method

- 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



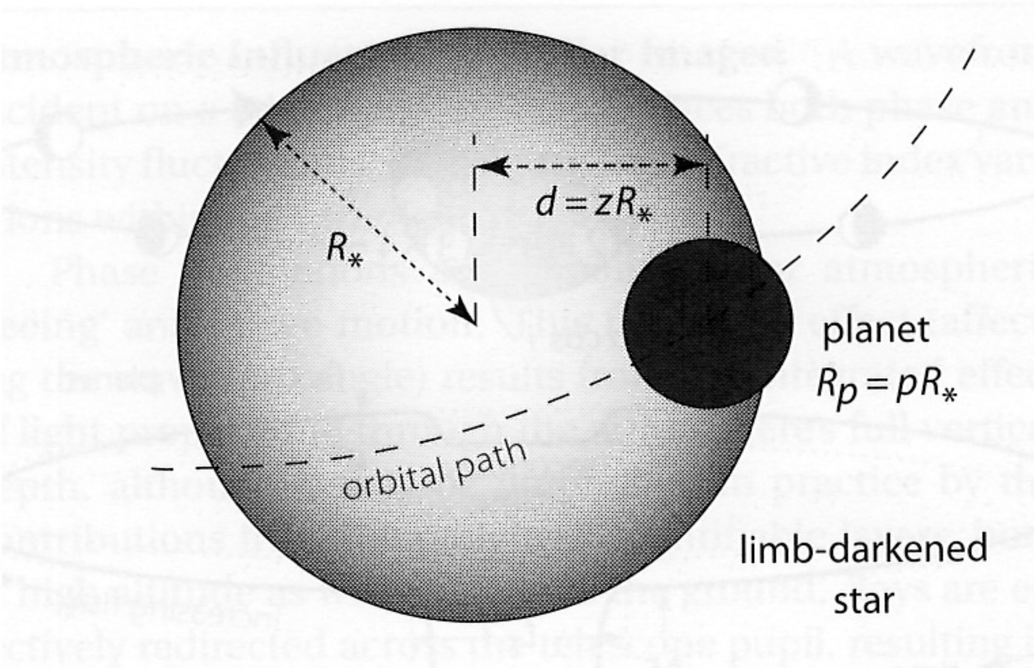
  - Impact parameter: projected (angular) distance between the planet center and the center of the stellar disk:

$$b = (a/R_*) \cos i$$



Transit method

- 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 limb darkening effects, the depth of the profile is:

    $\Delta F_r \cong (F - F_{\rm tr}) / F = (R_{\rm p}/R_*)^2$

    F: stellar flux outside the transit

    $F_{\rm tr}$: stellar flux during the transit (minimum of the light curve)

    $R_{\rm p}$: planet radius

    R_*: stellar radius

  - One can derive the planet radius in units of the stellar radius

Transit method

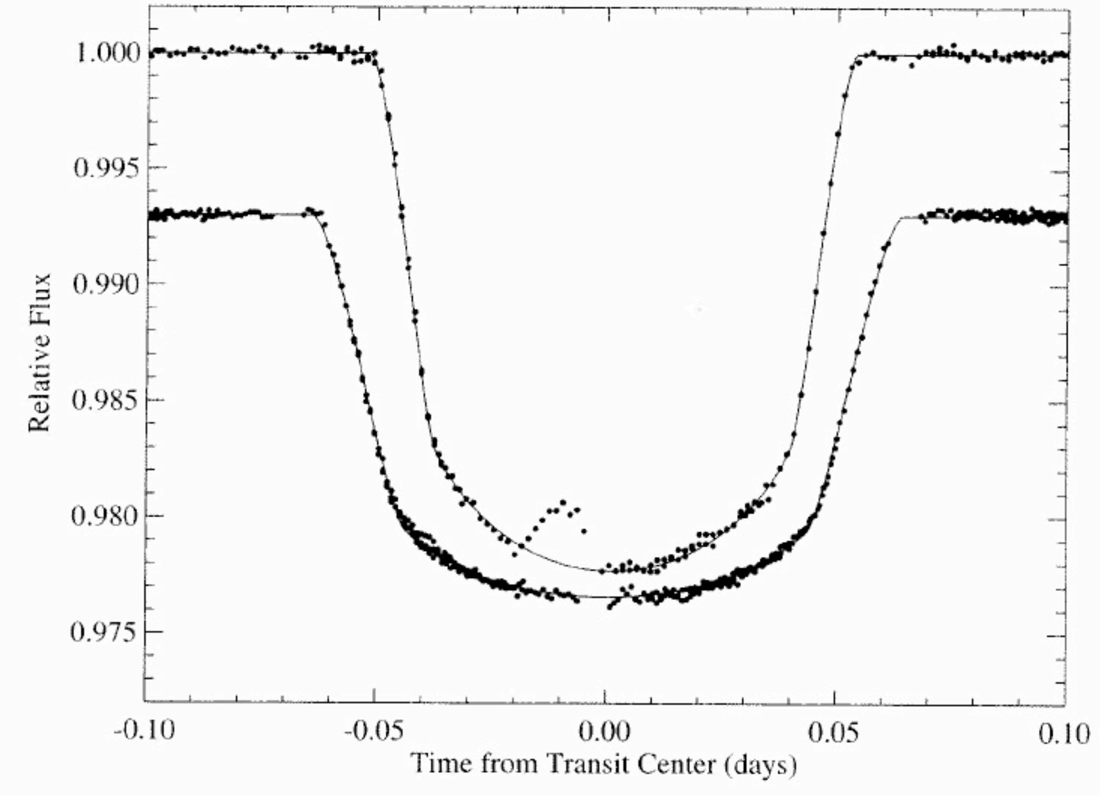
- Magnitude of the effect

  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 $R_p=R_{Earth} \Rightarrow \Delta F_r=0.01\%$

Requires a high photometric accuracy

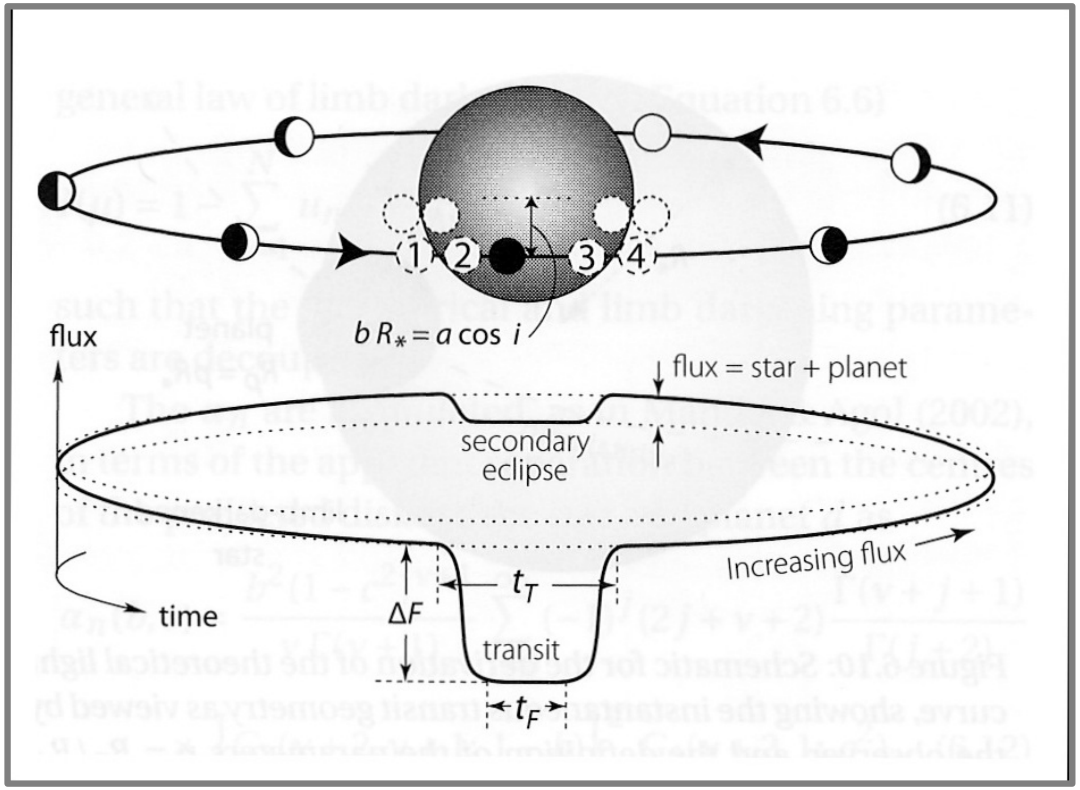


Transit method

- 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 orbital period, P, impact parameter, b, orbital inclination, i, and stellar radius, R_*
  - Setting i=90^o and b=0, and using a relation between stellar masses and radius, the duration of the transit for a circular orbit is numerically

$$t_T \approx 13 \left(\frac{M_\star}{M_\odot}\right)^{-1/2} \left(\frac{a}{1\,\mathrm{AU}}\right)^{1/2} \left(\frac{R_\star}{R_\odot}\right) \text{hours}$$

  - In the case of a solar-type star, this gives a total transit interval of ~25 h for a Jupiter-type orbit and 13 h for an Earth-type orbit

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 R_*/a

    R_*: stellar radius; a: orbital semi-major axis

    Typical value of the geometric probability:

    $p_{\rm geom} \sim 0.0045\ (1\ {\rm AU}/a)\ (R_*/R_\odot)$

    Charbonneau et al. (2007)

- Time probability
  - The probability of observing a transit at a given time scales with $t_{\rm T}/P$, where $t_{\rm T}$ is the duration of the transit phase (see previous slide)

Transit method

- Selection effects
  - The transit signal increases with $(R_p/R_*)^2$

    Easier to find large planets orbiting small stars

  - Number of detections 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

    Also the time probability favours detections of planets with short orbital periods

    These selection effects reinforce the bias due to the temporal baseline of the observations

    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

Transit method: false positives

- Problem of the false positives
  - due to the presence of eclipsing binaries that may lie in the bakground, in the same direction of the host star
- Need of follow-up programs
  - Doppler method is the safest way to confirm candidates

    However, the star should be sufficiently brilliant to perform high resolution spectroscopy (problem for Kepler targets)
- Search for stellar binaries
  - With adaptive optics

    However, 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 from the analysis of high resolution spectra, where they produce a characteristic splitting of the stellar lines, which varies according to the binary orbital period

Kepler mission

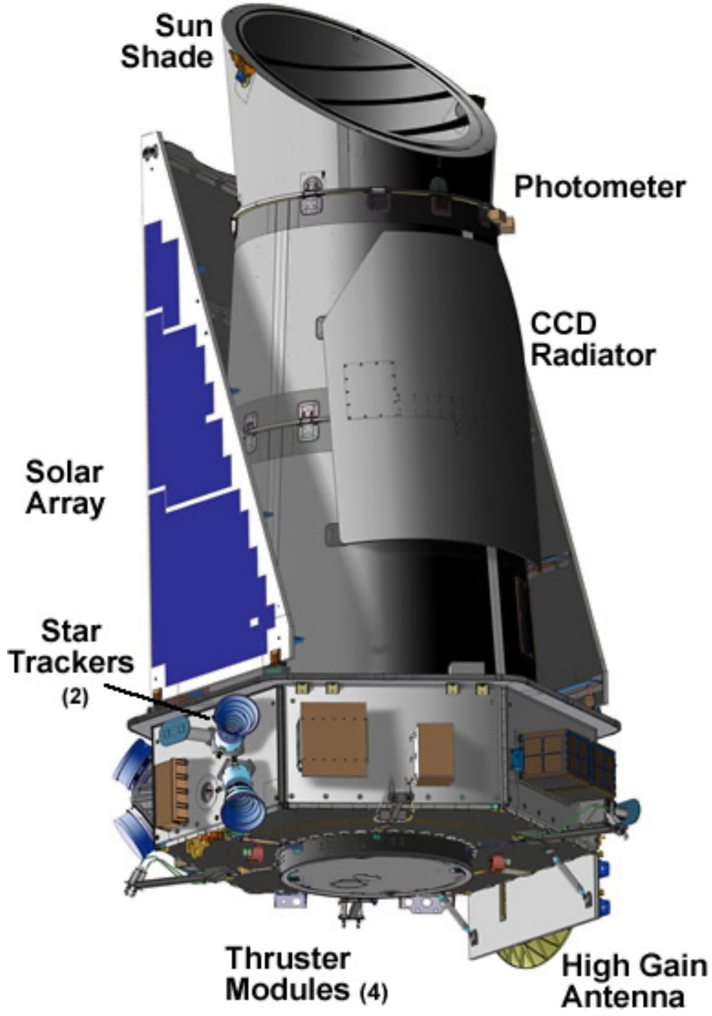
http://kepler.nasa.gov

- 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 σ level in 6.5 hours of integration

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

- Updated tables of the orbital/planetary parameters

  http://kepler.nasa.gov/Mission/discoveries/

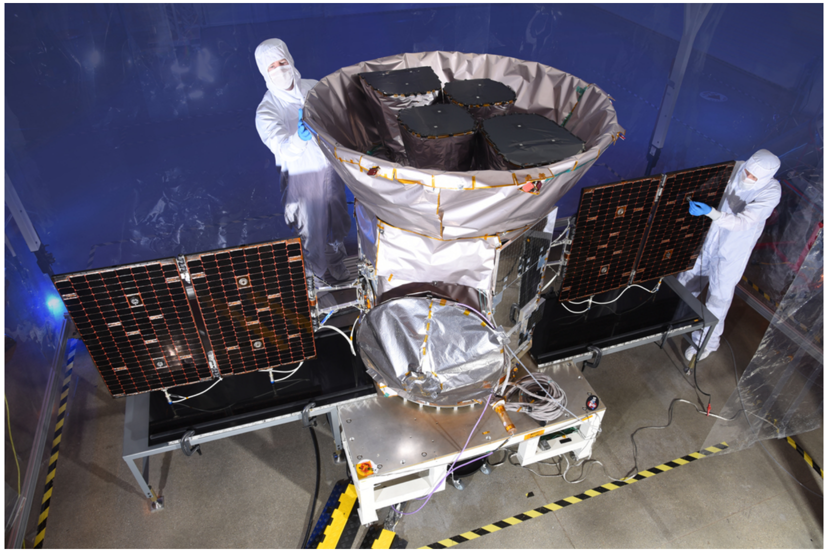


Tess mission

https://heasarc.gsfc.nasa.gov/docs/tess/

- The Transiting Exoplanet Survey Satellite (TESS) is a NASA mission that is performing an all-sky survey to search for planets transiting nearby stars

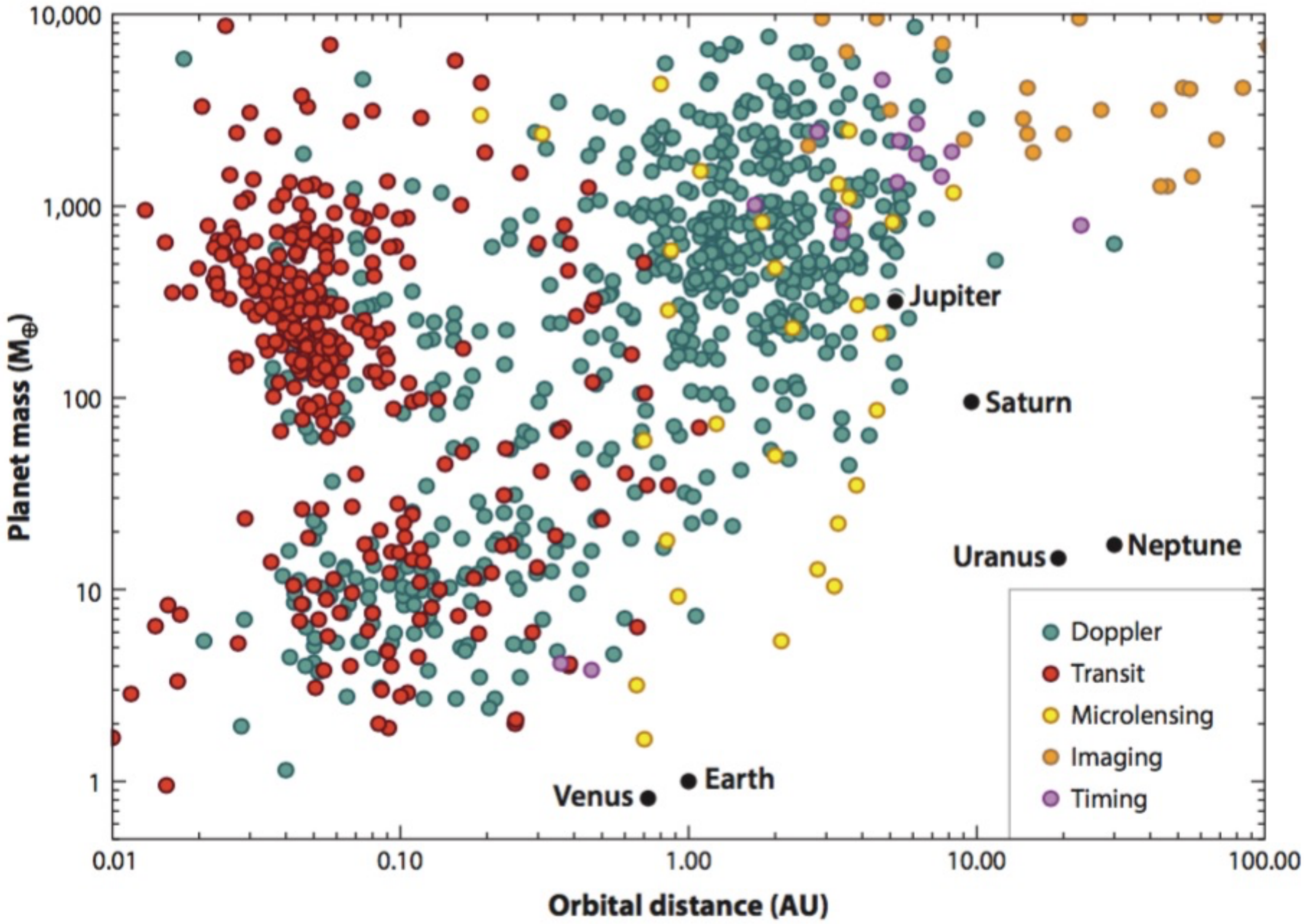
- The primary goal of TESS is to discover planets smaller than Neptune that transit stars bright enough to enable follow-up spectroscopic observations that can provide planet masses and atmospheric compositions



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



Transit method

Summary of detections (January 2018)

Confirmed detections with primary transits
2780 planets in 2083 planetary systems

Candidates
2407 planets in 2235 planetary systems