THE TRANSIT LIGHT CURVE

Introduction

The transit light curve gives astronomer a wealth of information about the transiting planet as well as the star. It is only for transiting exoplanets that astronomers have been able to get direct estimates of the exoplanet mass and radius. With these parameters at hand astronomers are able to set the most fundamental constraints on models which reveal the physical nature of the exoplanet, such as its average density and surface gravity. As mentioned above the transit events do not just give information about the exoplanet, but quite often also information about the star. With telescopes capable of high precision photometry, transit curve anomalies can say something about the activity of the star. An example of this is when an exoplanet crosses star spots (Fig. 1) [source]. This can be seen in the light curve as a small increase in flux due to the light of a cooler part of the star being blocked out.

With a very high precision light curve with a high Signal to Noise (S/N), the light curve can also be used to infer the presence of other planets in the system. Perturbations in the timing of exoplanet transits may be used to infer the presence of satellites or additional planetary companions [source,source].

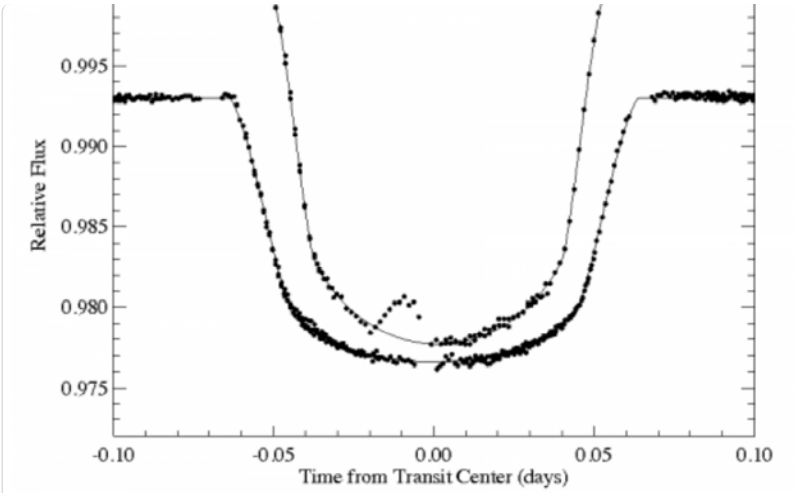

Fig. 1: Transit light curves of two transiting exoplanets, TrES-1 (top) and HD 209458 (bottom, offset by -0.007 for clarity). Since TrES-1 has a shorter orbital period and smaller size, the transit duration as well as the duration of ingress and egress are shorter. The hump in the TrES-1 data is likely due to the planet occulting one or more star spots on the surface of the star.

Theory

Kepler's Third Law

From Newton's second law of motion and Newton's law of universal gravitation one can derive an elegant relationship between the semi-major axis (The longest diameter of an ellipse) of the orbit, a, and the period of the exoplanet. This law is known as Kepler's 3^{rd} Law. Mathematically the law is written as:

$$\frac{a^3}{P^2} = \frac{G(M_* + M_p)}{4\pi}$$

Here G is the gravitational constant and a the distance between the exoplanet and the star. As the period, P, is easily determined from observations and using the fact that in most cases the mass of the planet is much less than the mass of the star $M_p \ll M_*$ one can solve for the semi-major axis:

$$a \approx \left(GM_* \left(\frac{P}{2\pi}\right)^2\right)^{1/3}$$

Having both the period and the semi-major axis one can estimate the orbital speed (assuming a circular orbit) to be:

$$v = \frac{2\pi a}{P}$$

Determining the radius of an exoplanet

The shape of a transit light curve gives astronomers a wealth of information about an exoplanet. One of the simplest things to estimate is the radius of the planet R_p, determined by the amount of blocked star light. As the exoplanet transits in front of the host star, star light is blocked and a dip occurs in the transit light curve. The size of this dip in brightness is estimated by simply looking at the fraction of light that the planet blocks:

$$\frac{\Delta F}{F} = \frac{R_P^2}{R_*^2}$$

F is the star flux whilst ΔF is the observed change of flux during the transit. This equation assumes the stellar disc has a uniform brightness. As we will see in the section about limb darkening, this is not the case, but as a first estimate this relationship works quite well. To determine an accurate value of the radius of the planet, R_p, one has to fit transit curves (using analytic formulae [source]) which are subject to the estimates of the stars mass and radius (M_*, R_*) and stellar limb-darkening coefficients.

What is truly special about this estimate is that we immediately have an idea of the size of the exoplanet in terms of the size of the host star. If the radius of the host star is known, one also knows the radius of the planet. For this to work we assume the exoplanet system is viewed from an interstellar distance so great that the distance to the exoplanet or host star can be considered equal.

Determining the transit duration

Once the radius of the star and thus the radius of the exoplanet is known, and having already measured the period and thus inferred the semi-major axis, it is possible to calculate the duration of the full transit T_{dur}. The full transit is measured as the duration of time when the planet obscures the disc of the star. The figures and derivations are adopted from “Transiting Exoplanets”, by Carole A. Haswell.

The total transit duration is heavily dependent on the impact parameter \$b\$ which is defined as the sky-projected distance between the center of the stellar disc and the center of the planet disc at conjunction (The point in the orbit where two objects are most closely aligned, as viewed from Earth). In other words, the distance from the center of the planet to the center of the star at mid-transit as seen by the observer (Fig. 2). For a circular orbit it is mathematically written as:

$$b = a \cos i$$

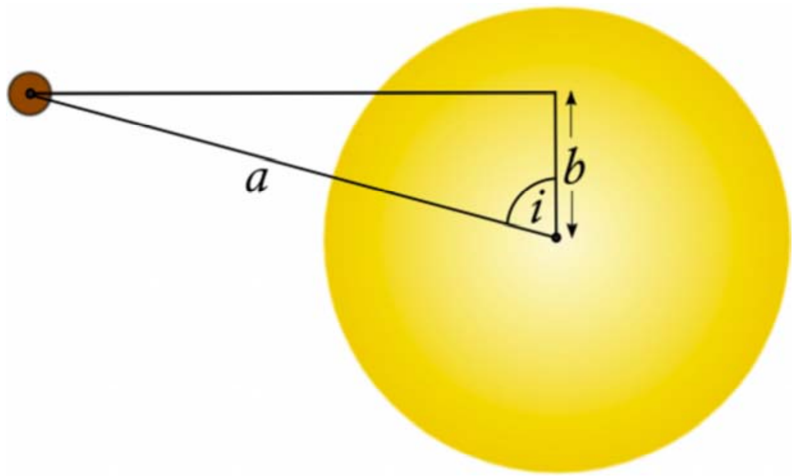

Fig. 2: Trigonometry showing the impact parameter b

The total transit duration also depends on how the planet crosses the star. If the exoplanet crosses the center of the stellar disc ($b = 0$), the transit duration is the longest. For ($b \neq 0$) the transit duration is shorter. With the help of Fig. 3 and using Pythagoras's theorem:

$$l = \sqrt{(R_* + R_P)^2 - b^2}$$

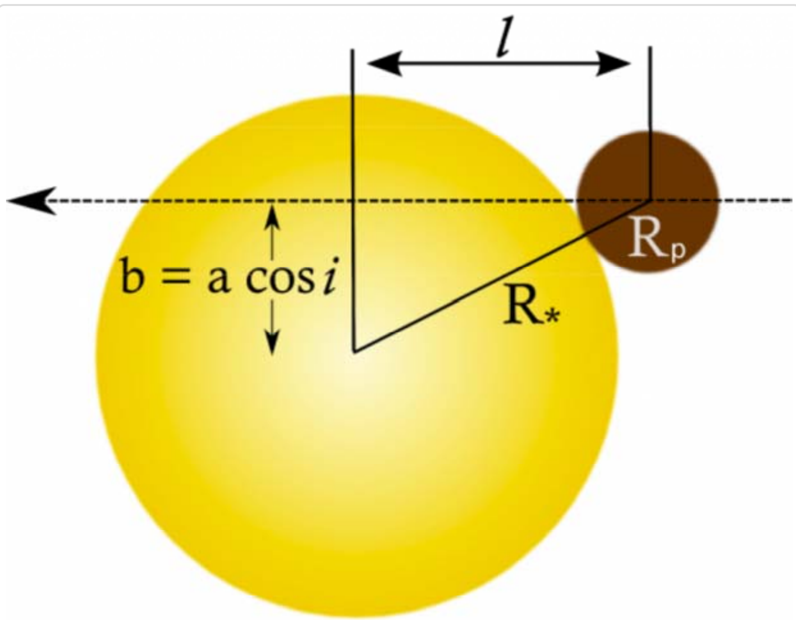

Fig. 3: By use of Pythagoras theorem the length l can be expressed in terms of the impact parameter b and the radii of the star and the planet.

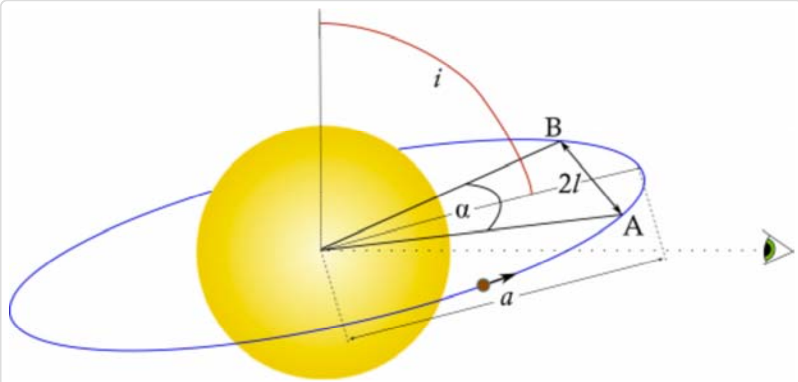

Fig. 4: During a transit the planet moves from point A to B on an orbit with inclination i. For an observer far away, the planet coveres the distance 2l. Assuming a circular orbit, the distance around a full orbit is 2*pi a where the planet moves along an arclength alpha a between points A and B. From the triangle formed between A, B and the center of the star, sin(alpha / 2) = l/a.

The length the planet travels across the disc of the star is $2l$ as seen by the observer. Looking at Fig. 4 we see that the exoplanet moves from A to B around its orbit, creating an angle α (measured in radians) with the center of the host star. With the assumption of a circular orbit, the distance around the entire orbit is $2\pi a$, where a is the radius of the orbit. The arclength between points A and B is αa and the distance along a straight line between A and B is $2l$.

From the triangle formed by A, B and the center of the star,

$$\sin\left(\frac{\alpha}{2}\right) = \frac{l}{a}$$

thus,

From the triangle formed by A, B and the center of the star,

$$T_{dur} = P\frac{\alpha}{2\pi} = \frac{P}{\pi}\sin^{-1}\left(\frac{l}{a}\right) = \frac{P}{\pi}\sin^{-1}\left(\frac{\sqrt{(R_*+R_P)^2-b}}{a}\right.$$

giving us the full transit duration.

Determining the inclination of the orbit, *i*.

Radial velocity observations of the host star alone are not able to determine the mass of the exoplanet alone. Instead it gives a value of $M_p \sin i$ known as the *minimum mass* which is estimated assuming the stellar mass, M_*, is known \cite{charbonneau-rev}. During a transit event, however, the orbital inclination, i, can be measured directly, thus giving an estimate of the exoplanet mass. This is done by studying the transit duration, T_{dur}, and ingress and egress times. A transiting exoplanet which does not pass across the center of the disc exactly ($b \neq 0$, $i < 90$), will have a shorter transit but longer in- and egress times, if compared to a planet that goes through the center of the disc ($b = 0$, $i = 90$). Having an estimate of the mass and the radius of the exoplanet, the average density and surface gravity can be estimated, giving hints to the structure and composition of the exoplanet.

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