ExoTransit_Visualization Guide, Version 1.1

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1 Overview

This tool helps visualize the pattern of light we see from a distant star when an object orbiting around it affects the star's light during part of the object's orbit - a transit. The object may be a planet or may be the companion star of an eclipsing binary star system. The user enters the model parameters in a GUI. After running the model, the transit curve and a figure of the system at maximum transit are updated. The model parameters are:

- `Star radius,` R_{star}, in units of the radius of the Sun
- `Limb Darkening Factor, LDF,` $(0 < LDF < 1)$
- `Planet radius` R_{planet} in units of $R_{Jupiter}$
- `Planet orbital radius` R_{orbit} in Astronautical Units (AU)
- `Planet central brightness` $B_{planet}(r = 0)$ at the planet disk center, 0 for a planet or > 0 for a binary companion star
- `Planet orbit inclination angle` θ_{inclin} (degrees)
- `Noise rms`

The maximum light blockage occurs if the object is a planet that is in the direct line-of-sight between us and the star. In this situation, the light reduction is approximately the ratio of the planet disk area divided by the area of the star disk, R^2_{planet}/R^2_{star}. The model requires that the planet be smaller than the star. The star and planet are assumed to travel around each other in a circular orbit of radius R_{orbit}. A constraint is imposed to prevent a non-physical situation where the would planet orbit within the star, $R_{orbit} > R_{star} + R_{planet}$.

Another requirement is that the plane of the planet orbit lies near the line of sight between the Earth and the star. This is characterized by θ_{inclin}, which is 0 if the planet orbit is exactly in our line of sight. A transit cannot occur if the inclination angle is too large.

The **brightness** of a star disk, $B_{star}(r)$, is the rate of photons observed per unit area of the star disk as a function of the distance r from the star disk center. The edge, or limb, of a star disk emits less light in our direction than the center (r = 0). The brightness of the star is set to 1 at the star disk center, $B_{star}(0) = 1$. The model includes a "limb-darkening factor", LDF, to help visualize how this affects transit shapes. Limb-darkening for the star is modeled by $B_{star}(r) = 1 - LDF \times (1 - \sqrt{1 - r^2})$. With this form, the brightness is 1 at the star disk center and is (1 - LDF) at the star limb. Limb-darkening can be disabled by setting LDF = 0.

The **luminosity** is the weighted average of the brightness in the star disk that is not occluded by the planet. In many cases, the measured luminosity is the sum of the star luminosity plus the luminosity of a companion star in a binary system. To model this, the "planet" central brightness, $B_{planet}(0)$, can be set to a value > 0. The companion star is assumed to have the same limb-darkening factor as the primary star.

The transit width is highly dependent on the orbital radius and the inclination angle of the orbital plane as viewed by us. Furthermore, there will be no transit if the inclination angle or the orbital radius is too large. The model requires that the inclination angle is less than arctan((R_{star} + R_{planet}) / R_{orbit}).

2 Results

The plot in the upper right of Figure 1 shows $B_{star}(r)$ using the default value of LDF = 0.4. This figure is updated when the user enters a different LDF and the "Update LDF Brightness Plot" button is clicked. The information displayed in the lower part of the figure is not defined until the "Run" button is clicked. The cartoon with the black background in the middle of the screen shows the size, position and brightness of the planet when it is directly in front of the star, at $\theta_{orbint} = 90°$ at the given inclination angle. The planet interior gray scale is normalized to the star brightness.

When the model is run, the planet is moved in 60 angle steps of 6 degrees, or one full orbit ($0° < \theta_{orbit} < 360°$). The brightness of the un-occluded sections of the star and the planet are summed for each step and displayed in the transit curve at the bottom of the screen. The maximum star-planet separation as viewed by us occurs when $\theta_{orbit} = 0°$ and 180°.

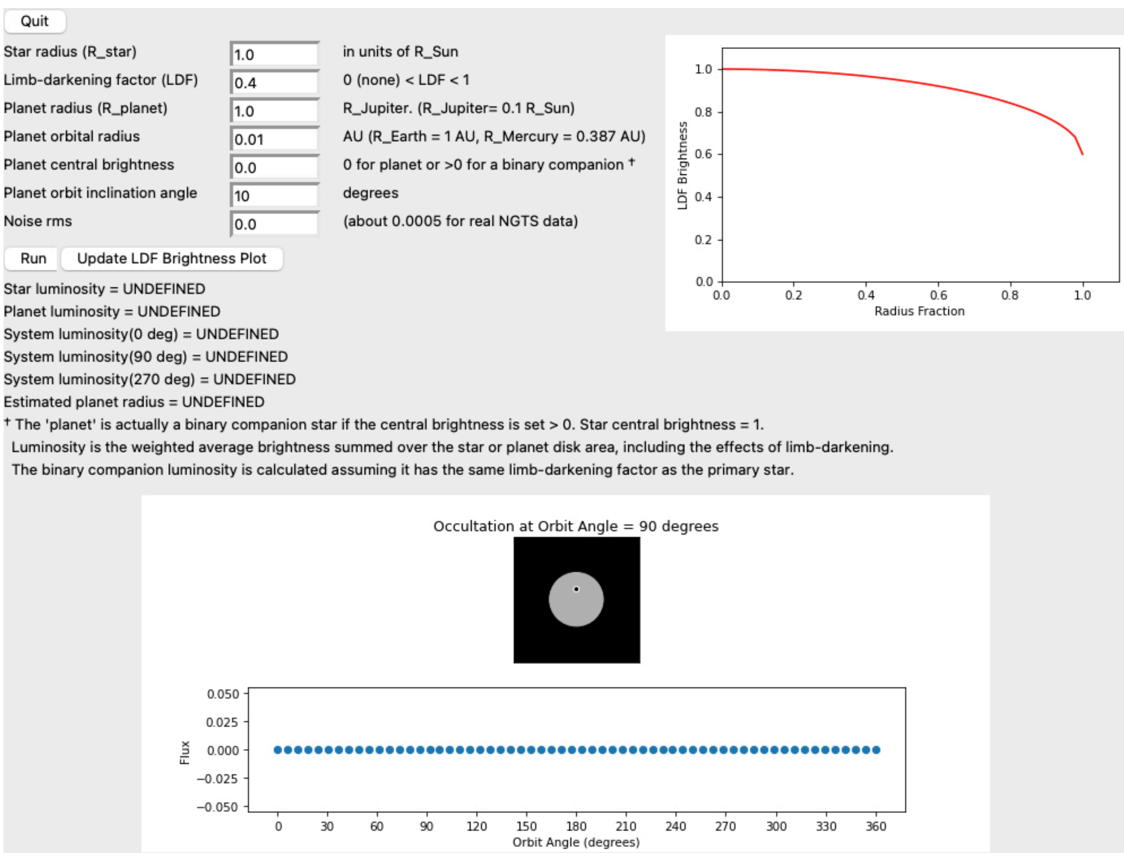

Figure 1: Screenshot taken when the tool is launched. Default system values have been loaded but the model has not been run.

After the Run button is clicked, the screen is updated as shown in Figure 2. The star luminosity is 0.866 at $\theta_{orbit} = 0$ instead of 1 due to limb darkening. It drops to 0.8566 at $\theta_{orbit} = 90°$. The relative size and position of the planet at maximum transit are depicted in the cartoon. The transit curve represents what would be seen if a Jupiter-sized planet orbited a Sun-sized star at a distance of 0.01 AU ($\sim 1.5 \times 10^6$ km).

Detailed results from the run such as the star and planet luminosities when there is no transit ($\theta = 0°$) and the total star-planet system luminosities when the planet is in front of ($\theta = 90°$) and behind ($\theta = 270°$) the star are displayed. An estimate of the planet radius using a relation between R_{star} and the drop in flux, or "dip", is shown when the inputs are valid for a planet, e.g. when the transit curve can be characterized as u-shaped or box-shaped.

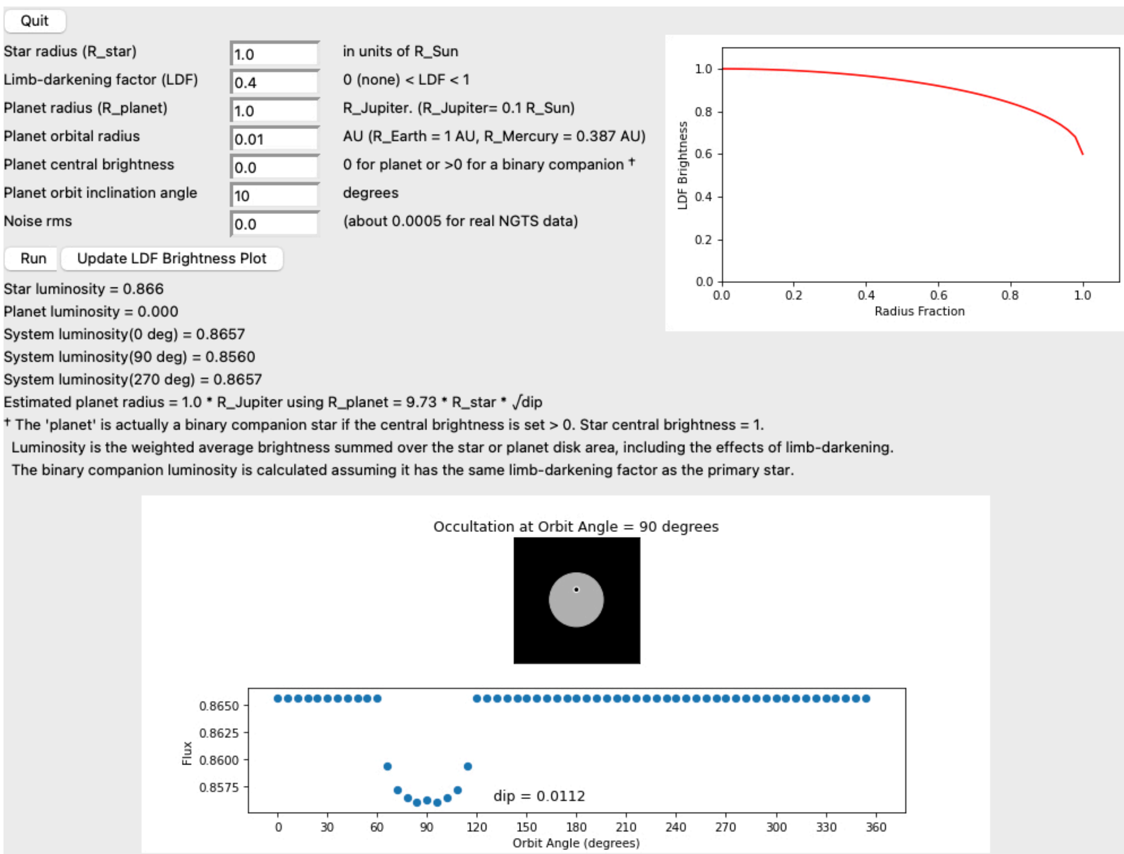

Figure 2: Default model conditions, a hot Jupiter, where the planet is the radius of Jupiter and orbits at a distance of 0.01 AU from a star like the Sun.

The effect of instrumental noise on the identification of a planetary transit can be visualized by setting the Gaussian noise rms > 0. A rough estimate of the NGTS noise rms is 0.005. Note that noise is added to the flux values in the transit curve after a transit model run has been made. Clicking the run button again without altering the model inputs does not force re-running the model but does change the random noise, In Figure 3, model inputs are unchanged except for the central brightness of the "planet" which is set to 1 to represent the companion star of an eclipsing binary system. The limb-darkening factor for the companion star has the same fractional radial dependence as that of the primary star, such that the primary star brightness is 0.6 at the edge of the primary star disk and companion star brightness is 0.6 at the edge of the companion star disk. The "primary phase" transit at $\theta_{orbit} = 90°$ is more u-shaped than the "secondary phase" transit at $\theta_{orbit} = 270°$ because the companion star radius is much smaller than the primary star radius.

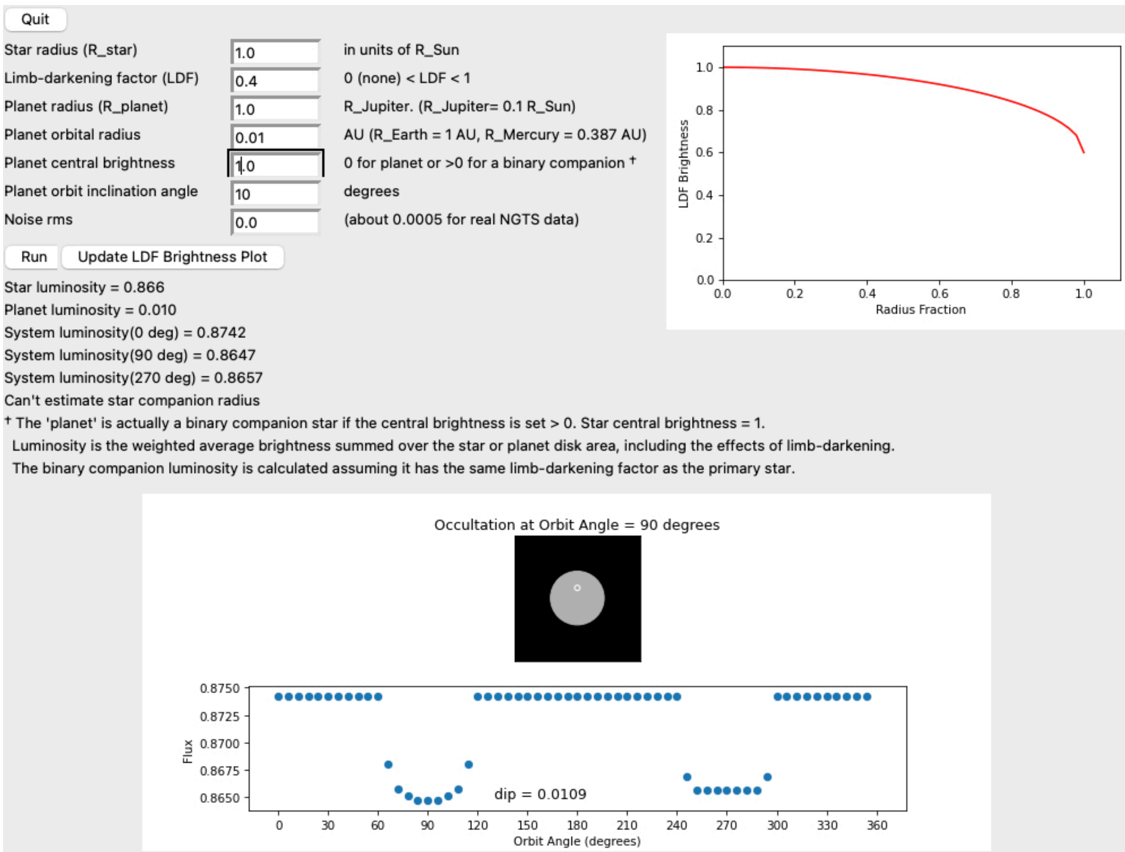

Figure 3: Binary star system in which the central brightness of the companion star is the same as the central brightness of the primary star.

3 Technical Details

The total intensity of the star and planet system for any value of θ_{orbit} is calculated by iterating over a grid of (x, y) points of size 0.01×0.01 over the area of a star disk with normalized radius $= 1$, resulting in 31,494 points. The grid size is reduced to 0.005 if the planet radius is $< 0.08\times$ R_{star}. If the distance between a point and the planet center, r_{planet}, is less than the planet radius, the planet brightness, $B(r_{planet})$, is summed, otherwise the star brightness, $B(r_{star})$, is summed. A second iteration is done over the planet disk if the planet brightness is > 0, requiring that the distance between each point and the star center is > 1.

This cpu-intensive calculation is only done when there is a true transit, i.e. when the distance between the star and planet in our field of view is less than $(R_{star} + R_{planet})$. When the star is not occluded, the system luminosity is the sum of the star luminosity and the planet luminosity.

The cpu time to simulate the transit of a large planet, using a grid size = 0.01, is 1.1 seconds on a MacBook Pro running Big Sur. The cpu time increases to 3.3 seconds when the grid size is set to 0.005.