ExoTransit_Visualization Guide, Version 1.0

Bruce Baller

December 12, 2021

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:

- The star radius, R_{star}, defined to be 1
- The star brightness, $B_{star}(0)$, defined to be 1 at the star disk center
- `Limb Darkening Factor, LDF,` $(0 < LDF < 1)$
- `Planet orbital radius` R_{orbit} ($> 1+R_{planet}$)
- `Planet radius` R_{planet} in the range 0.01 to 1
- `Planet brightness` $B_{planet}(0)$ at the planet disk center, 0 for a planet or > 0 for a companion star
- `Planet orbit inclination angle` θ_{inclin} (degrees)

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}, where R is the radius of the star or planet. Since the star radius, R_{star}, is set to 1, we require that the radial size of the planet, $R_{planet} < 1$. 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 planet would move within the star, $R_{orbit} > 1 + R_{planet}$.

A second 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 not uniform across the disk. The edge, or limb, of a star disk, (r $\sim$ 1), emits less light in our direction than the center (r = 0). In this model, 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 object. In many cases, the luminosity varies because the star-planet system is in fact an eclipsing binary star system. To model this, the "planet" central brightness, $B_{planet}(0)$, can be set to a value > 0. For simplicity, the companion star is assumed to have the same limb-darkening factor as the primary star. It's luminosity is calculated by summing $B_{planet}(r)$ =$B_{planet}(0) \times B_{star}(r)$.

2 Results

The plot in the upper right of Figure 1 shows $B_{star}(r)$ vs r using the default value of LDF = 0.6. 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°.

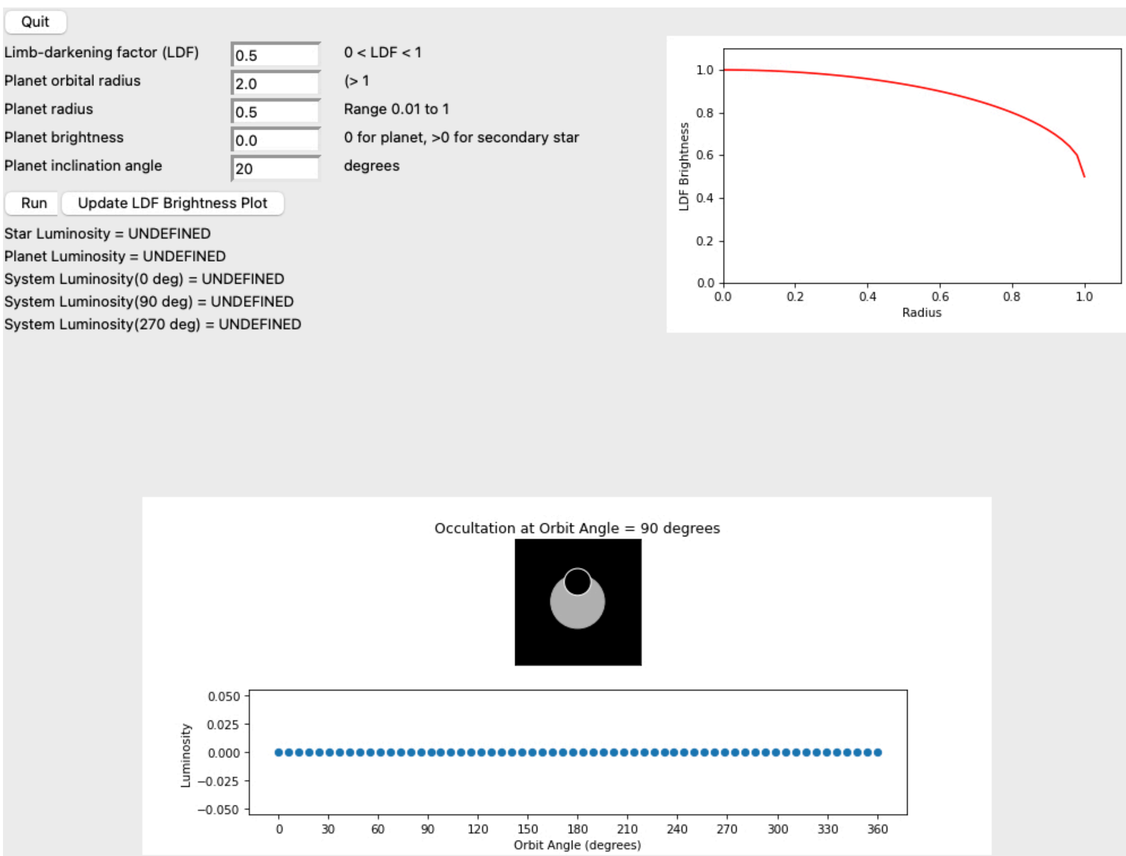

Figure 1: State of the GUI when the application is launched. Default system values have been loaded but the model has not been run.

After the user enters the desired inputs and clicks the Run button, the screen is updated as shown in Figure 2. The star luminosity is now 0.832 instead of 1 due to limb darkening. It drops from 0.832 at $\theta_{orbit} = 0$ where the star is not occluded to 0.676 at $\theta_{orbit} = 90°$ resulting in a significant decrease in the luminosity of $\sim 20\%$. The shallow slope of the transit curve is due to the large planet diameter and small orbital radius.

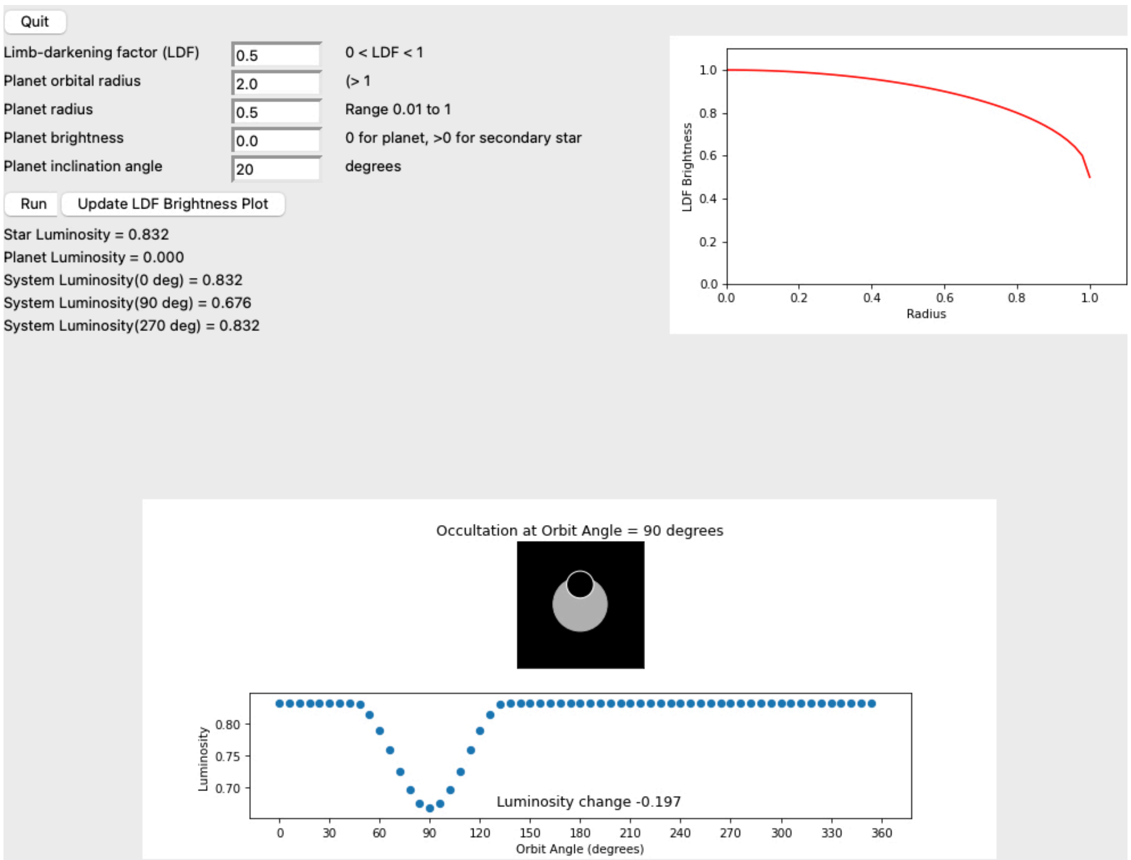

Figure 2: Default model conditions, a hot Jupiter, where the planet is one half the diameter of the star and orbits at a distance of 2 stellar radii.

A more common situation is that the planet is smaller and further from the star. Here we set the planet orbit at 4 stellar radii and the planet radius at 10% of the star radius. The dip in the luminosity is much smaller, 1.2%, and narrower.

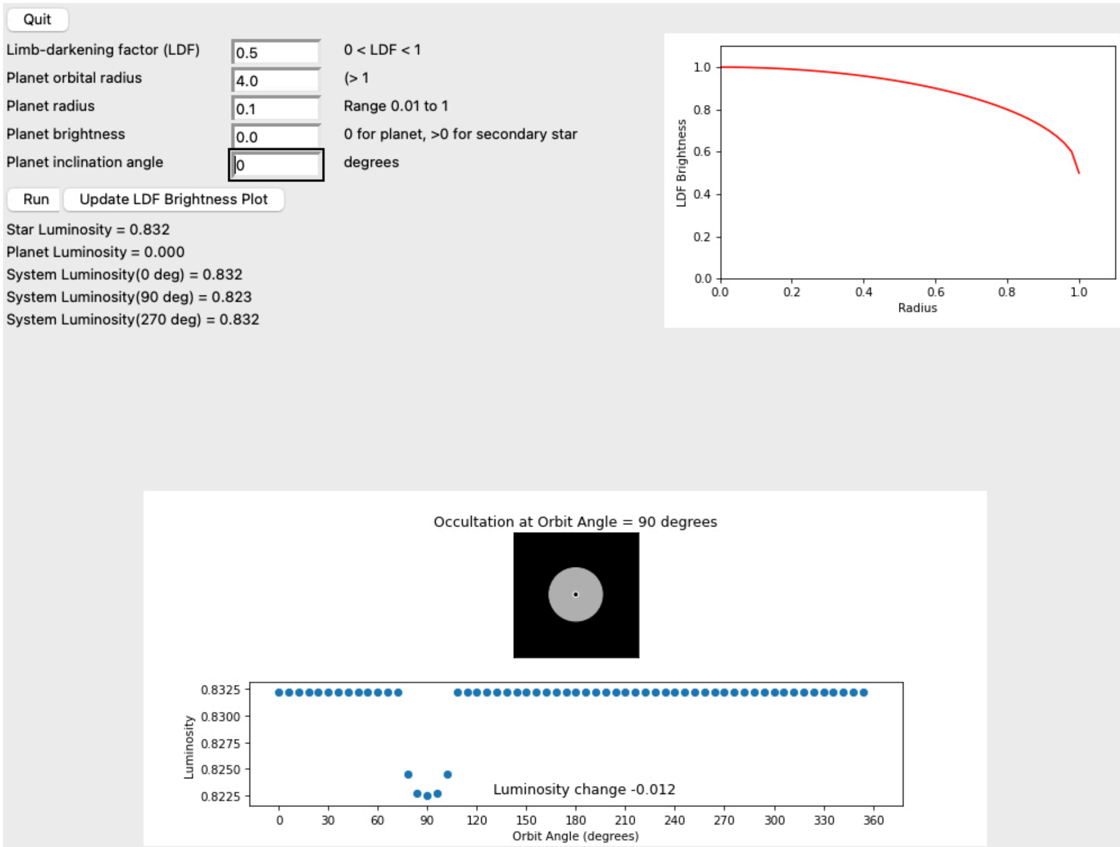

Figure 3: Run results for a planet of 10% of the star radius at a distance of 4 stellar radii.

2.1 Eclipsing Binary Star Systems

Next we set the "planet" radius to 0.8 and set the planet central brightness to 1, the same as the star, and run the model again. The results in Figure 4 shows two transits. The system luminosity is 1.365 when there is no transit. It drops to 0.875 at the first transit when the companion star is in the front of the main star and drops to 0.890 in the second transit when the companion star is behind the main star. The slight minimum luminosity difference is due to the interplay between the effect of a somewhat smaller companion star radius and masking of the limb-darkening effect of the primary and companion stars.

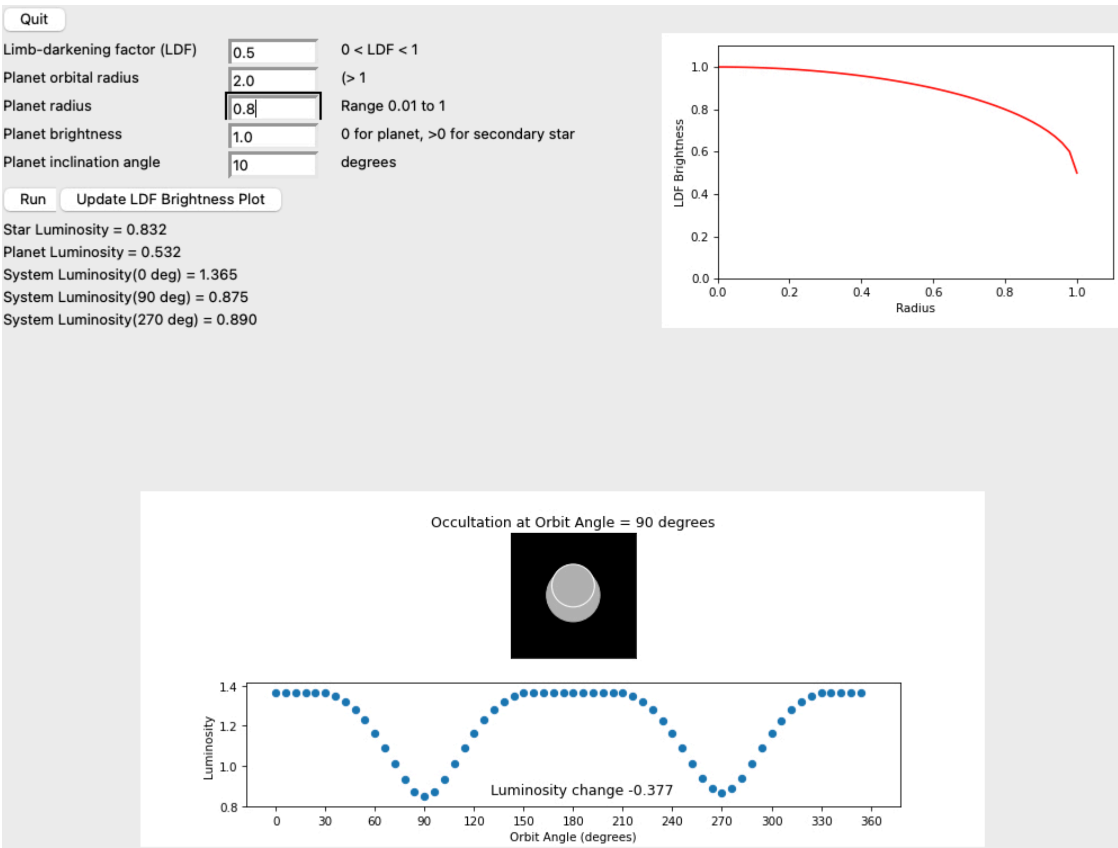

Figure 4: Run results for an eclipsing binary star system. The companion star radius is 0.8 of the primary star radius and the central brightness is the same as the primary star.

Finally we consider the case where the radius of the companion star is small but it is much brighter than the primary star. Figure 5 shows an example where the star radius is only 20% of the primary star radius but it is twice as bright at it's center. The drop in luminosity when the companion star is behind the planet in the second transit is considerably deeper than it is in the first transit when it is in front. The second transit is more box-like due to the small size of the companion star.

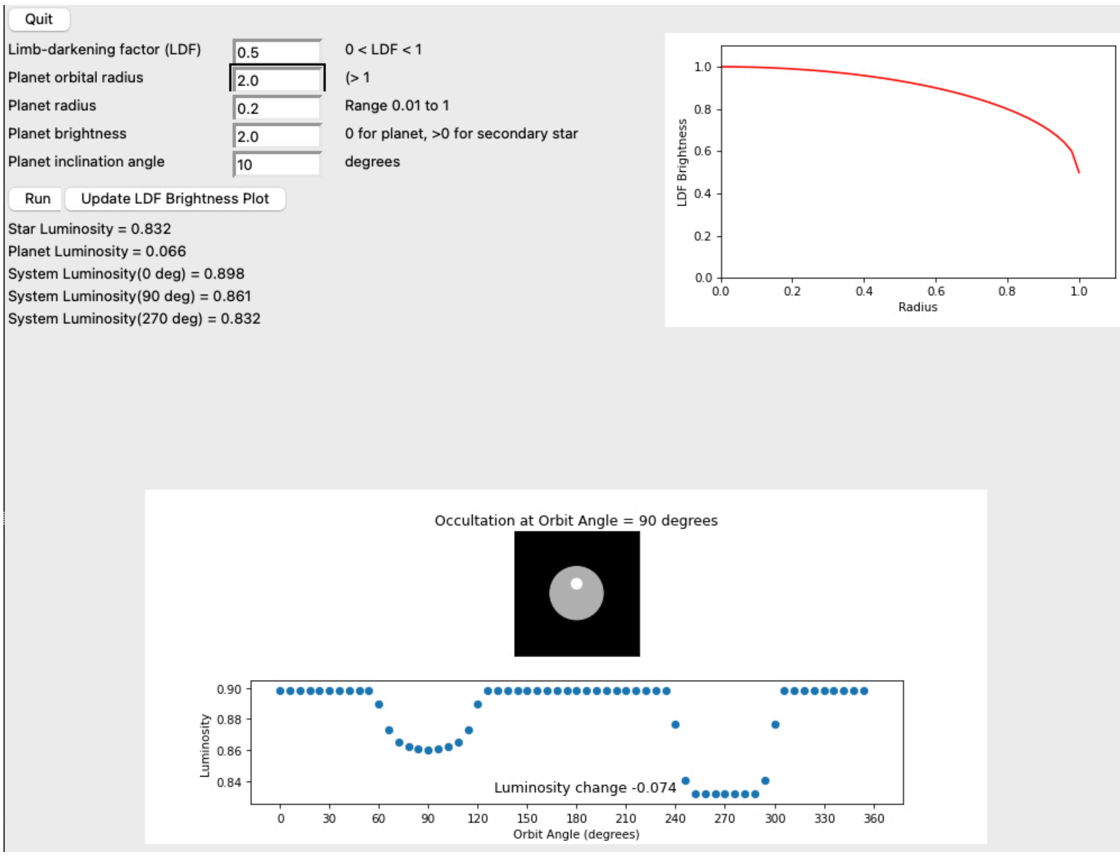

Figure 5: fig5

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 $\times$ 0.01 over the area of the star disk, resulting in 31,494 points. If the distance between a point and the planet center is less than the planet radius, the planet brightness is summed, otherwise the star brightness 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. Note that there is not an overall normalization of the transit curve.

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 (1 + R_{planet}). When the star is not occluded, the system luminosity is the sum of the luminosities of the star and planet.