I.M.A.G.E.R.: A Gravitational Microlensing Visualization Tool

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Abstract

For the final project of this class, we focus on the concept of gravitational lensing and its application in the field of exoplanets. Specifically, we present the method of exoplanetary detection and characterization utilizing the microlensing method. We are able to create I.M.A.G.E.R. (Images of Microlensing And Gravitational Einstein Rings), a python interactive program that allows for the user to manipulate the multiple parameters that alter the observed microlensing event. I.M.A.G.E.R. provides a visual representation of possible lensing events to further develop an intuition for the high utility and applications of gravitational lensing through an interactive GUI.

1 Introduction

In this class, various intriguing and developing scientific theories have been presented. It is important in the process of learning to not only understand the material and equations but to transform that towards the scientific application in current astronomical studies. In this report, we explain the phenomena of gravitational lensing and its application in the growing field of exoplanets. Additionally, we will discuss the python program that was created to provide a visual for users to better understand the concept of gravitational microlensing.

In the following subsections we describe the significance of microlensing in the field of exoplanet detection and the mathematical theory behind gravitational lensing. In Section 2, we outline the python program we designed to help visualize a gravitational microlensing event. We then conclude in Section 3.

1.1 Exoplanet Detection & Characterisation

In the field of exoplanets, there are numerous ways to detect these celestial bodies. The most common method is by observing transiting events through photometry and radial-velocity method. Other less utilized methods include pulsar timing, direct imaging and, of course, gravitational microlensing. Due to the lower probability of observing microlensed events, this method becomes more difficult but a recent study [1]found that this method is great for finding Neptune-like exoplanets. This region, beyond the 'snow line' is where these scientist believe to be the most efficient region for planet formation and also the the most sensitive region for microlensing. This can be seen in Figure 1

[1]D. Suzuki, D. P. Bennett, T. Sumi, I. A. Bond *et al* 2016 *ApJ* 844 2

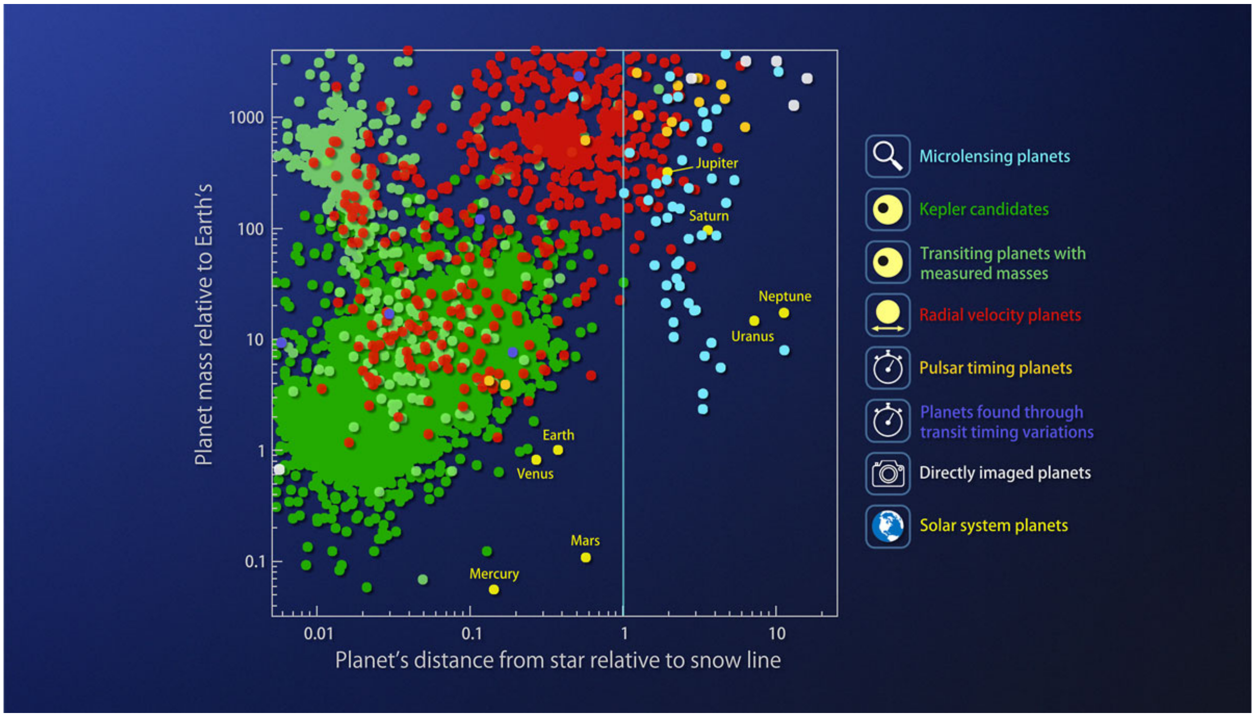

Figure 1: "This graph plots 4,769 exoplanets and planet candidates according to their masses and relative distances from the snow line, the point where water and other materials freeze solid (vertical cyan line). Planets are shaded according to the discovery technique listed at right."[2]

Gravitational microlensing allows for scientists to detect smaller, more distant exoplanets as this method is more sensitive, in comparison to transit photometry which is great for close, larger exoplanets around dimmer stars. This is why gravitational microlensing is an important method that is growing in significance as it builds off of the Kepler, K2 and now, TESS (Transiting Exoplanet Survey Satellite). The upcoming WFIRST (Wide Field Infrared Survey Telescope) mission, launching in 2025, hopes to detect thousands of these exoplanets through gravitational microlensing.

An example of the specific feature of the light curve during the various stages of the lensing event can be seen in Figure 2. It is important to notice the additional image lensed by the exoplanet that causes sharp spikes in the light curve. These spikes also provide information on the size of the planet as given by the following mass ratio,

$$q = \frac{M_p}{M_*} \tag{1}$$

where M_p is the mass of the planet and M_* is the mass of the lens star.

[2]Courtesy of NASA Goddard Space Flight Center: https://exoplanets.nasa.gov/news/1399/neptune-mass-outer-planets-likely-common-around-other-stars/

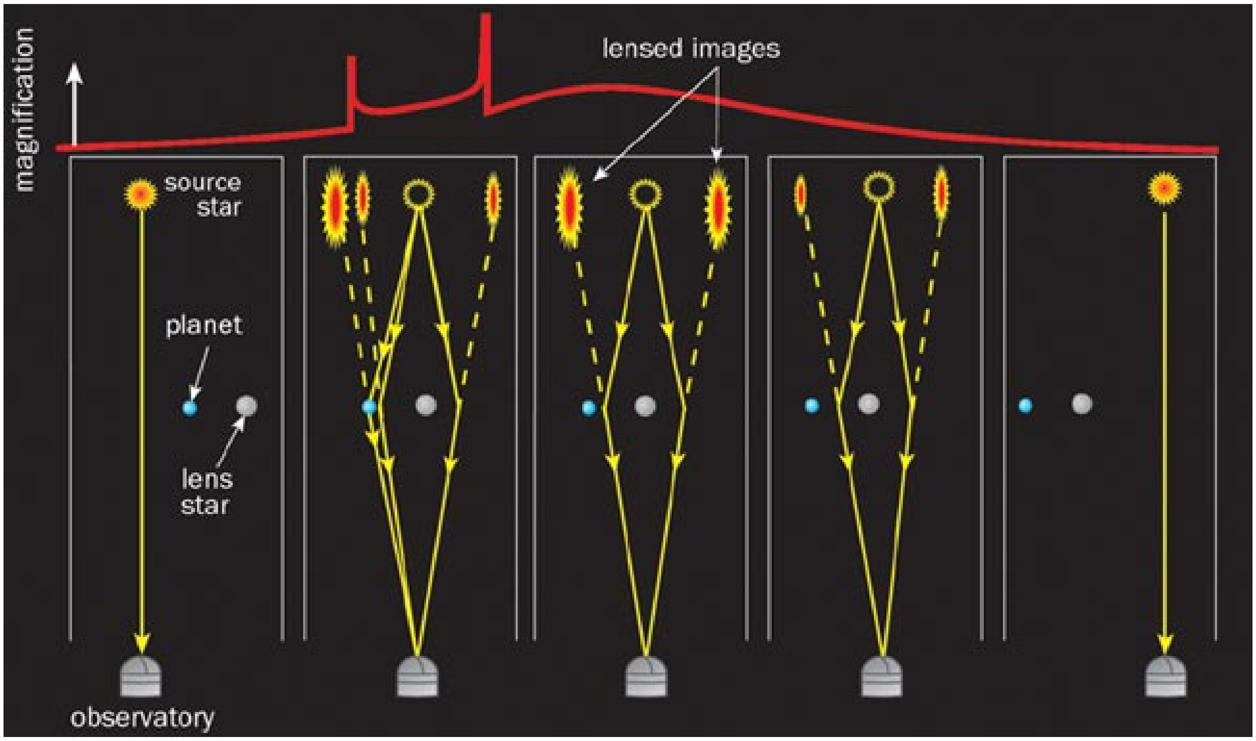

Figure 2: A stage by stage observation of a lensing system with the presence of an exoplanet as it crosses infront of the source. The light curve also shows the distinct peaks indicating the presence of the exoplanet in observations.[3]

1.2 How Does Lensing Work?

To understand how gravitational lensing works we must first refer to the equations. The most fundamental equations in gravitational lensing gives the Einstein radius θ_E,

$$\theta_E = \sqrt{\frac{4\pi G}{c^2}\frac{D_{LS}}{D_L D_S}} \tag{2}$$

where G is the gravitational constant, c is the speed of light, D_{LS} is the distance from the lens to the source, D_L is the distance from the observer to the lens and D_S is the distance from the observer to the source. This is the angular size of the ring where light gets warped. This can be seen in Figure 3.

[3]Photo taken from https://www.planetary.org/explore/space-topics/exoplanets/microlensing.html

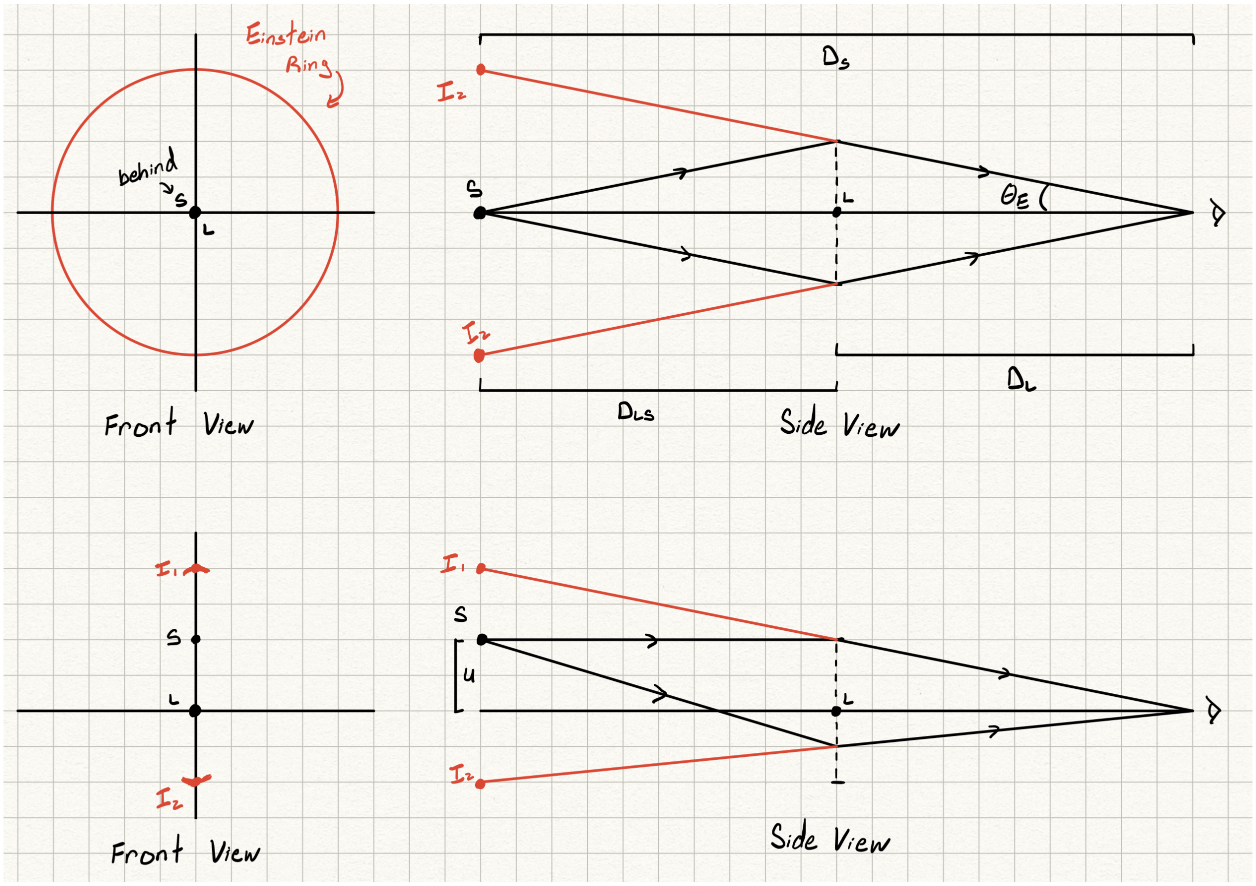

Figure 3: A sketch showing the geometric variables used in gravitational lensing. The top showing the scenario of an Einstein ring when the source is aligned with the lens, the bottom showing the source not aligned with the lens.

The next essential parameter to define is the impact parameter of the system, u,

$$u \equiv \beta \theta_E^{-1} \tag{3}$$

The impact parameter is the vertical distance between the source and lens. Knowing both u and θ_{E}, we can find the unitless variable β which is a constant for the specific u and θ_{E}.

If the impact parameter, u, is about 0, an Einstein ring can be seen as picture in Figure 4. This phenomena occurs only when the source object is directly behind the lens. If the source is not directly behind the lens, the observer will see two images with their respective magnifications as seen in the light curve.

Figure 4: A photograph of an Einstein Ring taken by the Hubble Space Telescope.[4]

The light bends due to the mass of the lensing object and creates two images of the source. The first image is the shorter distance where the source light only slightly bends over the lensing object. The second image of the source is where the light goes underneath the lensing object, then to the observer. The flux from this second image source is much less due to the magnitude of the warping of the light. The angle has to be perfect to allow for the light to hit the observer. The equation for the images, θ_+ and θ_- is written as follows,

$$\theta_\pm = \frac{1}{2}\left(\beta \pm \sqrt{\beta^2 + 4\theta_E^2}\right) \tag{4}$$

As the light from the source makes its way to the observer, it goes through a magnification process. Light from a single source has now been duplicated and multiplied from the light which would have gone past the observer, is now directed at the observer. To find the magnification of each image μ_+ and μ_-, we will use the following equation,

$$\mu_\pm = \left[1 - \left(\frac{\theta_E}{\theta_\pm}\right)^4\right]^{-1} = \frac{u^2+2}{2u\sqrt{u^2+4}} \pm \frac{1}{2} \tag{5}$$

The total magnification, μ_{tot} is the sum of the magnification of each image,

$$\mu_{tot} = \frac{u^2+2}{u\sqrt{u^2+4}} \tag{6}$$

The last equation essential to parameterizing a gravitationally lensed event is the Einstein crossing time. This is defined as the time it takes for the source to cross the Einstein ring as seen by the observer,

$$t_E = \frac{D_L \theta_E}{v_\perp} \tag{7}$$

where $v_\perp$ is the transverse velocity of the lensing system.

These variables are all utilized in the code for I.M.A.G.E.R. and will be the parameters that can be changed by the user to visual appreciate the effect of each parameter and the general proportionality of the relationships.

[4]Courtesy of ESA/NASA: https://hubblesite.org/contents/articles/gravitational-lensing

2 I.M.A.G.E.R.

I.M.A.G.E.R. (Images of Microlensing And Gravitational Einstein Rings) is a program that shows a star being lensed by another object in space as well as showcase what the lightcurve would look like if an exoplanet was present in the lensing system. This allows for the user to appreciate how Astronomers can detect and characterize exoplanets using gravitational microlensing. I.M.A.G.E.R. creates interactive plots which allows the user to set the values of the parameters defined in the previous section. Note that this program is dependent on the following packages/modules, *numpy, matplotlib, ipywidgets* and *IPython.display.*

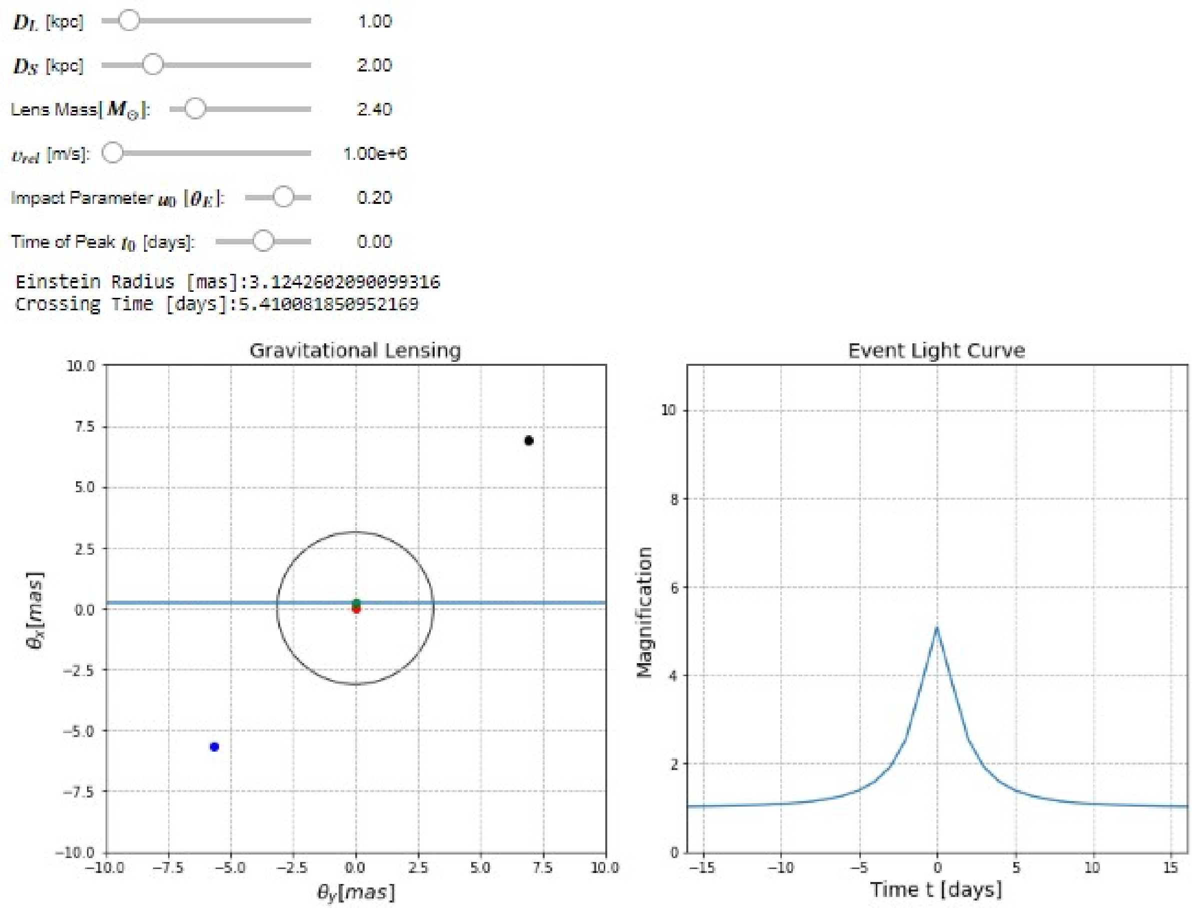

Figure 5: A snapshot of the resulting GUI and plots from the I.M.A.G.E.R. code for a simple single lens event. The interactive sliders are at the top with two plots below showing the lensing event from the perspective of the observer looking at the source and lens, and the lightcurve.

As seen in Figure 5, the plot on the left shows the created Einstein ring, the source and the 2 projected images. The red dot is the source object, the green dot is the lensing object, and the black and blue dots are the lensed images of the source object. The second plot on the right shows the source magnification over time. The user is able to see how different values of each variable would increase or decrease the magnification as well as manipulate the specific time of the peak magnification.

In the second section of the I.M.A.G.E.R. program, a second scenario is presented where there is an exoplanet in the lensing object's system as seen in Figure 6. The additional presence of this object, represented by the yellow dot, alters the light curve as the exoplanet also acts as a lens when crossing infront of the source. Due to this additional lensing, there are multiple peaks seen in the light curve. It is the presence of these additional peaks that lead astronomers to detect exoplanets or a binary system.

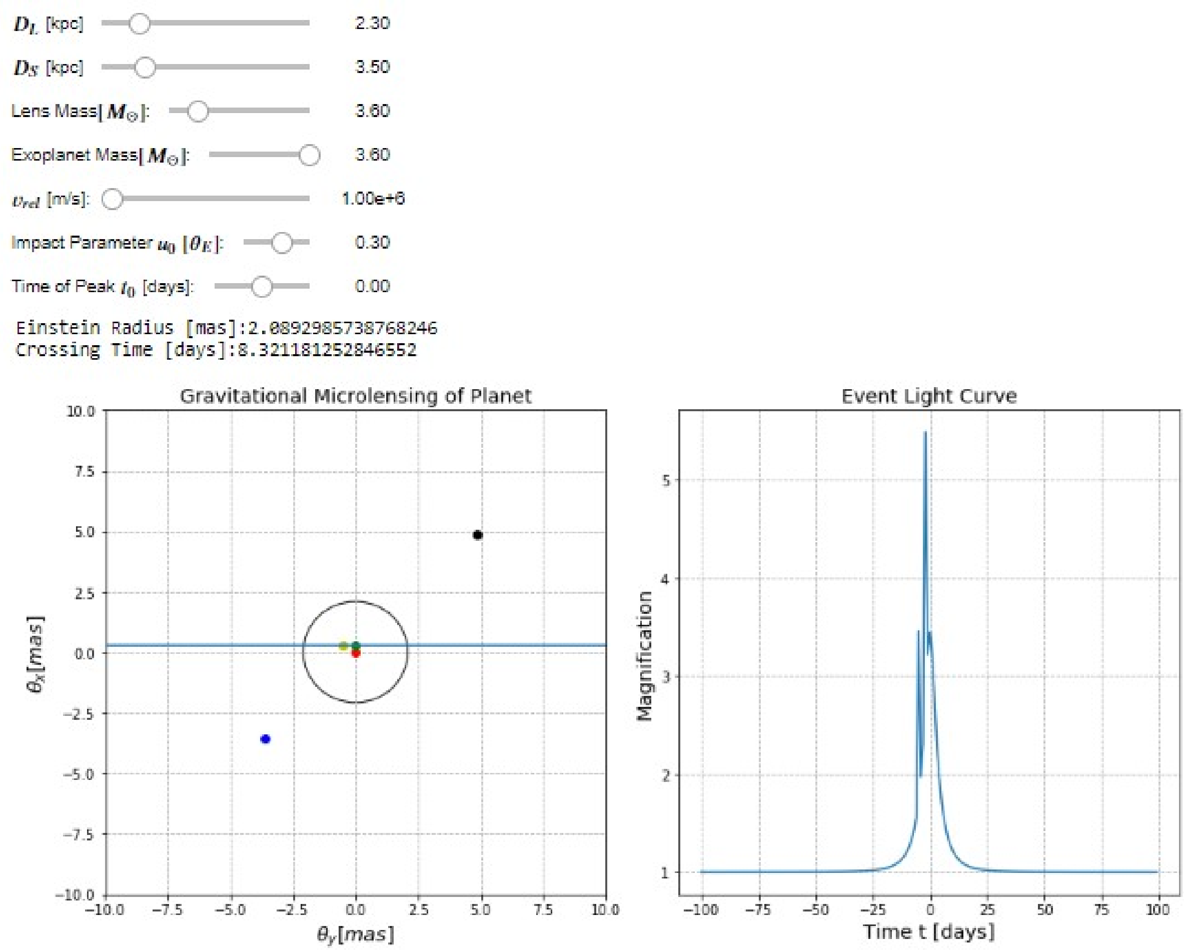

Figure 6: The I.M.A.G.E.R. code for a lensing system with the presence of an exoplanet. Note the additional peaks created by this object in the light curve on the right plot.

I.M.A.G.E.R. can be a very useful tool to help in visualizing simple cases of gravitational lensing and provide an intuition as to how exoplanets are detected in the light curve of real observations. Future work on I.M.A.G.E.R. could provide a more accurate light curve produced by the exoplanet when transiting. Additionally, it would be useful to be able to add a time animation of the plots to show the movement of the images as the lens and source approach each other.

3 Conclusion

In this final project, we are able to create I.M.A.G.E.R. to help visualize the mathematically presented idea in class of gravitational lensing. This tool aids in building an intuition for the relationship between the parameters that effect the lensing event. This project has also given an appreciation and insight as to the understanding and diagnosis of light curves seen in real observations and their significance. Additionally, this project has allowed us to go further to explore the current application of gravitational lensing to the detection of exoplanets. There are other applications of gravitational lensing that are used by cosmologist that are not covered in this report but this work serves as an example of the importance of this phenomena. We now anticipate the launch of WFIRST to see the full scope of the spectrum of exoplanets thanks to gravitational microlensing.

References

[1] Massimo. Microlensing.

[2] Jonathan Pritchard. Gravitational lensing.

[3] J. Yee S. Anderson L. Vu R. Tam Y. Tsapras S. Gaudi R. Street, S. Cross. Microlensing source.

[4] Penny D Sackett. Microlensing exoplanets.