If You Give the Sun a Telescope: Imaging Alien Earths with Einstein Rings as Seen by the Solar Gravitational Lens

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1 Abstract

Contemporary methods of directly imaging exoplanets have yielded the first images of their kind, though none have yet allowed humanity to view the surface of an alien world. Resolving the fine structure of objects as small and distant as exoplanets requires a telescope the proportions of which current technology is incapable of producing.One solution, a telescope concept known as the Solar Gravitational Lens (SGL), consists of a modest optical telescope aligned with the Sun at a heliocentric distance of ~550au. When a target exoplanet is aligned in syzygy with the SGL, it will produce a perfect Einstein ring about the Sun — contained within this distorted image will be high-resolution optical and spectroscopic data from the planet's surface and atmosphere.Though the geometrical and optical and properties of the SGL have been well-determined in the literature, no method has yet been presented for reconstructing source images from the Einstein rings the SGL will produce. Here we present `SunTracer`, a general-relativistic lensing simulation which produces images with the same properties as the SGL, meant to provide a means of generating a set of test images for a forthcoming reconstruction method. Creating such a set of images is an important first step towards solving the problem of deconvolution, as the pristine alignment conditions required of the SGL result in a relatively constrained parameter space. These conditions are too perfect to have been observed naturally, thus no astronomical images yet exist that could serve as realistic test data for SGL reconstruction. We anticipate that `SunTracer` will aid our own future work in this area.

2 Background

Gravitational lensing & Einstein rings

- Light rays are deflected by the gravitational field of massive bodies. This results in a phenomenon known as *gravitational lensing*, in which light from a bright source (a star, a galaxy, etc.) behind another can be bent around it, similar to a refracting telescope.

- Lensed images can take many forms depending on the mass distribution of the lens and the alignment of the source, lens and observer. If the three are in perfect alignment (in *syzygy*), what they produce is known as an *Einstein ring*, a perfect circle of light around the lens.

- This ring is a warped image of the source — if the equivalent of a "reverse lensing" operation were performed on it, it would be seen in its original form. Syzygal alignment provides the highest magnification of the source by a significant margin.

The Solar Gravitational Lens

- The *Solar Gravitational Lens* (SGL) is a telescope concept which seeks to take advantage of this unparalleled power by utilizing our own Sun as a gravitational lens, aligning a telescope with the Sun and a target exoplanet to yield high-resolution images of their surfaces.

- Figure 1 shows the geometry of the SGL. The Sun's minimum focus exists at ~550au, but focusing extends far past this point along its focal line, **F**. Optical properties of the SGL, like magnification and FOV, scale with functions of $\mathbf{D_L}$ (the distance between the telescope and the lens) and $\mathbf{D_{LS}}$ (the distance between the lens and the source).

- For example, at $\mathbf{D_L}$ = 750au, the SGL would have a collecting area equivalent to a ~90km telescope and angular resolution equivalent to a radio telescope with a baseline of ~12 Earth radii (Turyshev et. al. 2019). This configuration would make resolving an Earth-size planet at $\mathbf{D_{LS}}$ = 30pc a relatively simple task.

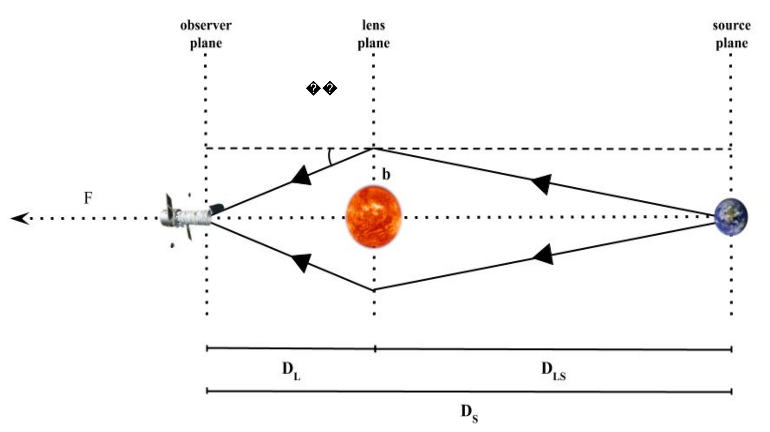

***Figure 1**: Diagram of the SGL. Here we show what is called the thin lens approximation, in which it is assumed that light (the arrowed-lines) is bent at just one point (the lens plane, which intersects the Sun) and is bent at an angle α perpendicular to the lens plane.*

3 Methods

General-relativistic raytracing

- Adapted a raytracing algorithm for simulating the path of light under the influence of the Sun's gravitational field (Jorge Jiménez-Vicente, 2016) which produces physically accurate images of geometric lensing.

SGL-specific optical properties

- Simulated images are run through a convolution pipeline which adds point-spreading (Figure 3).

- Magnification (μ) decreases quickly with offset from the focal axis (ρ) and increases with wavelength (λ). Offset sensitivity is inversely proportional to λ (Figure 4).

- Area of the source image present in a given Einstein ring depends on both $\mathbf{D_L}$ and $\mathbf{D_{LS}}$.

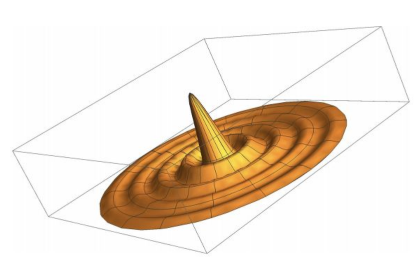

***Figure 2**: Airy disk of the SGL. Peaks show how light from a single point bleeds into surrounding points, known as point spreading.*

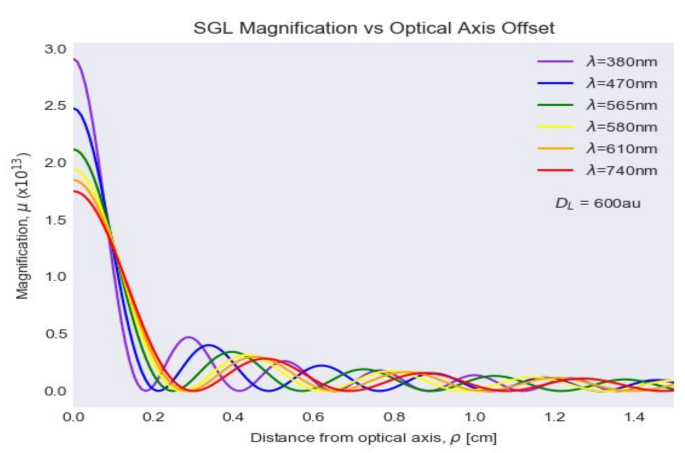

***Figure 3**: Magnification at visible wavelengths. Sensitivity to ρ increases with wavelength, meaning that observations at redder λ allows for less precise telescope pointing at the cost of magnification.*

4 Results

- `SunTracer` succeeds in tracing light rays originating from points on the source to their proper mapping on the image of the Einstein ring. A diagram of this map is shown in Figure 4; the existence of this mapping in the simulation is most evident in the top of Figure 5.

- Point spreading effects are added the lensed images in Figure 5 post-production and simply blur the images. Because the optical properties of the SGL have been studied in detail by Turyshev and Andersson, the PSF is well known and can be removed fairly easily. Thus, purely geometric lensing is the biggest takeaway from the simulation, which is what is shown in Figure 5.

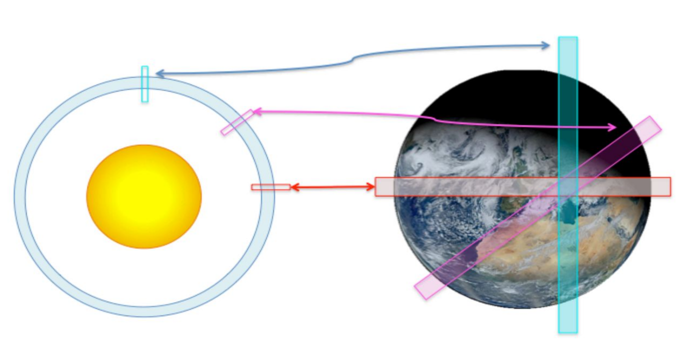

***Figure 4**: Diagram of how a pixel on the planet maps to its Einstein ring when lensed (Landis 2016). This effect is demonstrated best with a 2D gaussian in Figure 4.*

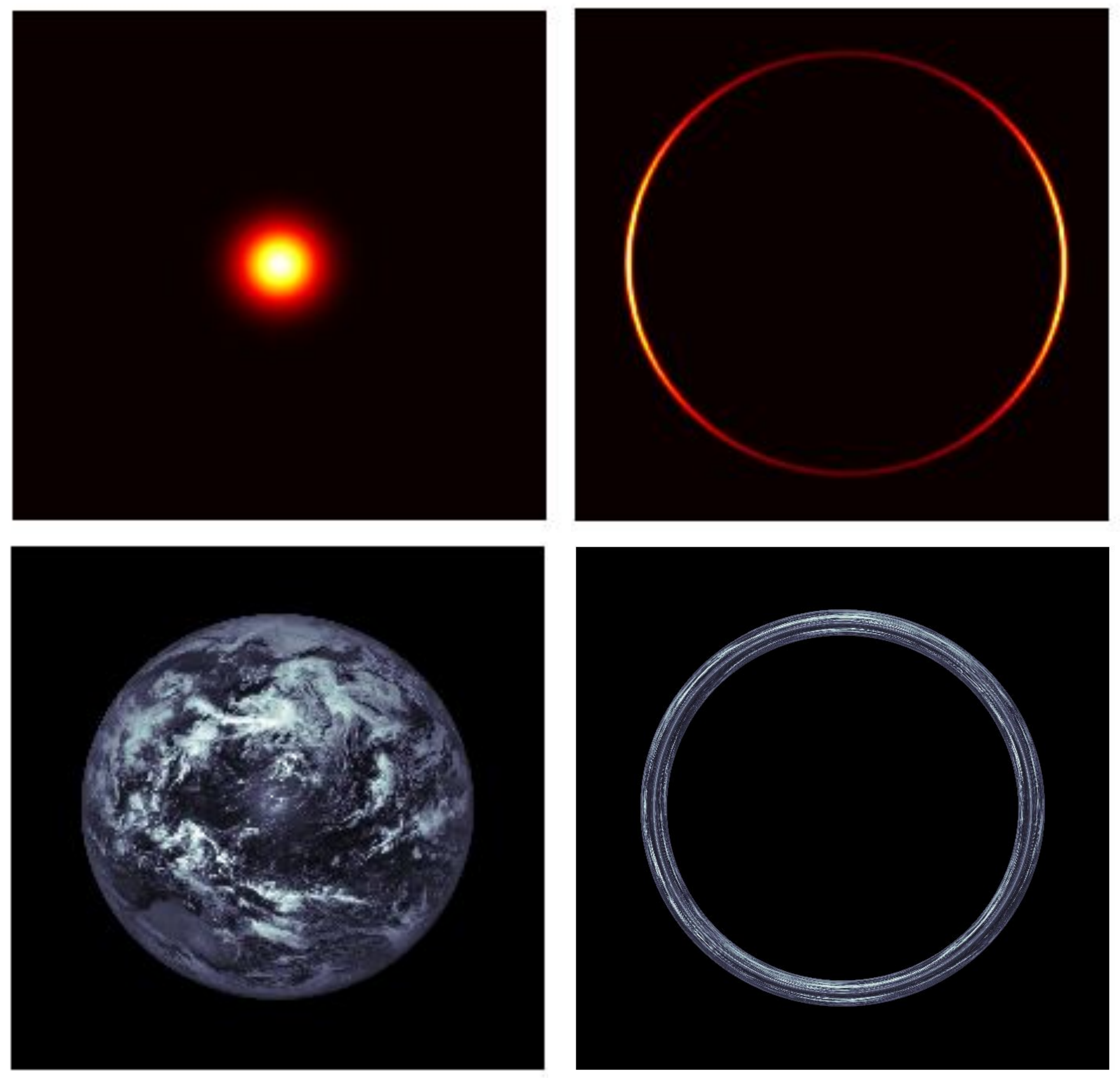

***Figure 5 (right)**: A 2D gaussian source with its lensed image (top) and a satellite image of the Earth (NASA EPIC/DSCOVR) with its lensed image (bottom). The SGL alignment used in calculating the top figures is slightly skewed to emulate Figure 4. These images were produced by `SunTracer`, but include no point-spreading. The geometric nature of the SGL's relativistic optics is most obvious in the plots shown, especially the topmost subfigures.*

5 Future Work

Deconvolution

- What we want from the SGL is not a collection of Einstein rings, but the images contained within them. `SunTracer` was written to provide a set of images with known sources for a pipeline which will derive the source image from the distorted ones. The next step, and the ultimate goal of our research, is to provide a general method for this deconvolution process.

Spectroscopy

- The primary goal of creating the SGL is to find a habitable exoplanet outside of our own solar system. In general, high-resolution spectroscopic data will be more valuable than visual data in the search for life, as it can be used to precisely identify biosignature gases present in the atmosphere. We intend to pay special attention to spectroscopic data, both in the simulation and the deconvolution algorithm.

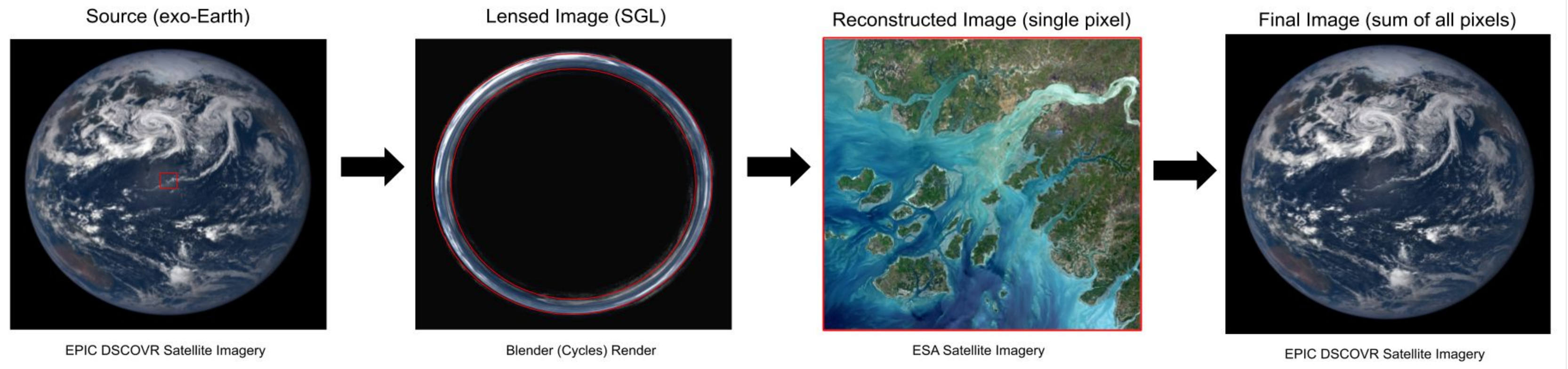

***Figure 6**: A basic outline of deconvolution. A source exoplanet is lensed by the Sun and an image is taken by the SGL, representing a single pixel in the final image. This is repeated, spanning every pixel on the planet, and each pixel is deconvolved and the source image is reconstructed by their sum.*

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