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Putting gravity to work: Imaging of exoplanets with the Solar Gravitational Lens

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The remarkable optical properties of the solar gravitational lens (SGL) include major brightness amplification ($\sim 10^{11}$ on the optical axis, at a wavelength of 1 μm) and extreme angular resolution ($\sim 10^{-10}$ arcsec). A deep space mission equipped with a modest telescope and coronagraph, traveling to the focal area of the SGL that begins at $\sim$ 548 astronomical units from the Sun, offers an opportunity for direct megapixel imaging and high-resolution spectroscopy of a habitable Earth-like exoplanet. We present a basic overview of this intriguing opportunity.

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1. Introduction

One of the celebrated classical tests of general relativity was the deflection of light by the gravitational field of the Sun. The maximum angle of deflection, $1.75''$, is quite small; nonetheless, rays of light from a distant source grazing the solar surface on opposite sides of the Sun do meet at $\sim$ 548 astronomical units (AU) from the Sun[1,2] (see Figure 1).

Given recent developments in space exploration[3], it is possible, using already available spacecraft technologies and propulsion methods, for a deep space mission to reach this enormous distance after a few decades of travel time and continue operating there for many years while communicating with the Earth. This opens up an opportunity to utilize the solar gravitational lens (SGL) as an element of a

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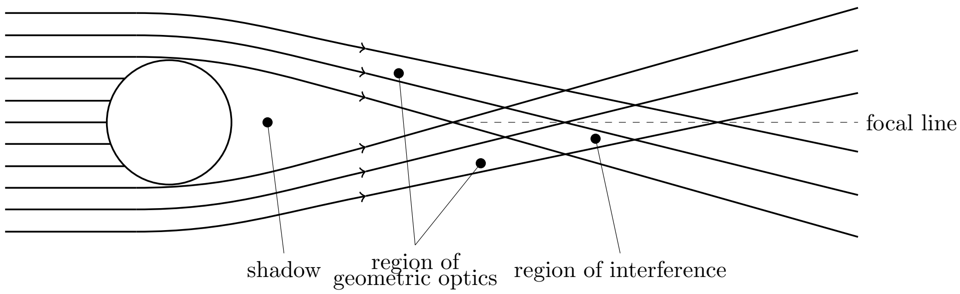

Fig. 1. Three different regions of space (not to scale) associated with the SGL: the shadow, the region of geometric optics, and the region of interference where the focal line is located.

large-scale astronomical telescope, designed to obtain a high-resolution image of a specific preselected target.

This intriguing possibility is of special relevance to the exploration of possible life-bearing planets outside the solar system. Direct detection of light from an Earth-like exoplanet is a challenging task. The angular size of this object is very tiny, requiring extremely large apertures or interferometric baselines. Light contamination from the parent star can only be handled using advanced coronagraphs. Detecting the extremely faint light of an exoplanet over a noisy background requires exceptional pointing stability over very long integration times. Obtaining a detailed image of an exoplanet is simply not possible using current or foreseeable methods of optical astronomy.

In contrast, the SGL offers a powerful natural instrument with extraordinary capabilities[2]. Its light amplification is $\sim 10^{11}$, sufficient to detect light from a selected faint, distant source of scientific interest, such as an exoplanet. Its angular resolution of ~ 0.1 nas (nanoarcseconds) allows imaging an Earth-size exoplanet at megapixel resolution up to 30 parsecs (pc) from the solar system[4].

The Sun's remarkable optical properties are not without considerable challenges. The distance to the beginning of the focal line is, as of the time of this writing (early 2019), about four times the distance to our most distant existing spacecraft, Voyager 1. Even with a coronagraph, observations would have to be conducted on the background of the solar corona. This increases the integration time needed to obtain the required signal-to-noise ratio (SNR). As an optical lens, the SGL also suffers from spherical aberration and astigmatism, causing a blurred image that must be processed using yet-to-be-developed deconvolution algorithms. Furthermore, the target is not static: the exoplanet is moving along its orbit, it rotates, its illumination changes, even its surface properties (e.g., cloud formation, vegetation) may vary.

Nonetheless, these challenges can be overcome using existing, available technologies and proven techniques[3]. Herein, we focus on one of the core challenges of using the SGL as a telescope: image formation and image reconstruction.

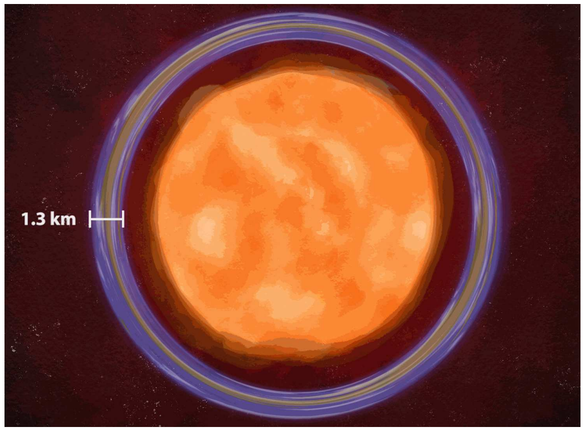

Fig. 2. Einstein ring with thickness of 1.3 km (not to scale) around the Sun formed by light from an Earth-like exoplanet.

2. Imaging with the SGL

The finding of a life-bearing exoplanet will be a scientific discovery of momentous significance. Such a planet will likely be identified at first as a single-pixel image, barely suitable for spectroscopic analysis, through which the presence of life is inferred. The desirable natural, but very difficult next step would be to obtain a higher resolution image of the exoplanet.

The angular diameter of an Earth-like exoplanet at 30 pc is $\sim 1.4 \times 10^{-11}$ rad. Resolving the disk of this planet as a single pixel would require a telescope array with a baseline of $\sim$ 74.6 km. A megapixel image, with a thousand pixels to one side, would require a baseline of $\sim 1.5 \times 10^5$ km, or about twelve times the diameter of the whole Earth, which is clearly not feasible.

In contrast, a 1 m telescope placed beyond 550 AU from the Sun, on the focal line of the SGL and working in conjunction with it, has an effective light collecting area of an $\sim$ 80-km aperture optical telescope. Its angular resolution is similar to that of an optical interferometer with a baseline that is twelve times the Earth's radius. While building an optical telescope with the SGL's capabilities is far beyond our technological capabilities, using the SGL to capture a megapixel image of an exoplanet is within reach.

Given an Earth-sized target with a diameter of $\sim 1.3 \times 10^4$ km, located at $\sim$ 30 pc, its image is projected by the SGL to a cross-sectional area with a diameter of $\sim$ 1.3 km. A telescope at the focal line of the SGL would see a faint Einstein ring around the Sun (see Figure 2). The telescope can be equipped with a coronagraph to block out light from the Sun itself and some of the solar corona. In a coronagraph simulation, we found that at a contrast of 2×10^{-7}, the leaked solar light is $\sim$ 5 times lower in intensity than the corona[3], effectively leaving the corona the main source of light contamination. This, of course, is not removable by any coronagraph

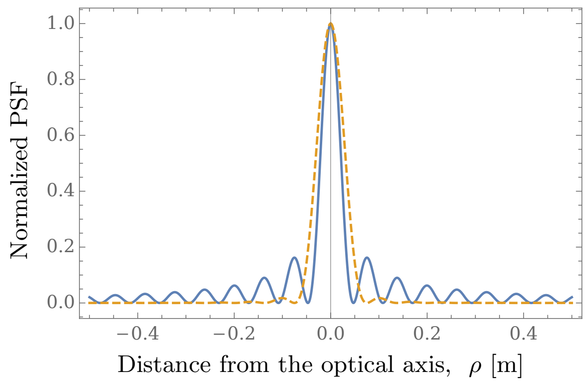

Fig. 3. Comparison of PSFs: the solid line represents the PSF of the SGL, the dotted line is for the traditional PSF. Note how the SGL's PSF falls off much more slowly.

because the Einstein ring is viewed through the corona.

The Einstein ring is bright enough to see over the noise background due to parts of the corona not obscured by the coronagraph, and other background sources of light (e.g., zodiacal light, transient events). As the telescope traverses the image plane in a direction perpendicular to the focal line, Einstein rings dominated by light from different parts of the exoplanet become visible. To construct a megapixel image, the observing telescope must be positioned in sequence at each pixel in the image plane, measuring the light intensity of the Einstein ring as seen from that pixel. Each ~ 1 m diameter pixel in the image plane approximately corresponds to a pixel diameter of ~ 10 km on the surface of the exoplanet.

The SGL suffers from spherical aberration. Its point spread function (PSF), which determines how light is projected from a point-like source onto the image plane, must be determined by a wave-theoretical analysis[2]. The PSF is quite broad, falling off much more slowly than the PSF of a typical lens (Figure 3). Consequently, as the Einstein ring is viewed from any pixel in the image plane, it combines light from not only the corresponding pixel on the surface of the exoplanet but also many adjacent pixels, leading to significant blurring. Additionally, the SGL suffers from astigmatism, due to the oblateness and rotation of the Sun.

Knowledge of the PSF makes it possible to apply deconvolution algorithms that enable reconstruction of the original image with high fidelity. To make this process work, a high SNR is required. This is where the extreme light amplification of the SGL plays its beneficial role, by offering, in combination with the coronagraph, a high SNR even over very short integration times.

Scanning the image plane one pixel at a time is time consuming. Take an exo-Earth at 100 light years away. Observing it with a telescope with $d = 1$ m aperture diameter having a realistic optical throughput, and accounting for the presence of various noise sources including solar plasma, interstellar dust, the SNR on a single pixel is estimated to be $\sim 10^3$ in 1 sec. Even inflating the per-pixel integration time to 120 sec to account for spacecraft slewing and re-pointing, the total integration time needed to collect the data for a megapixel image is ∼3.8 years[3]. This is well within the scope of a realistic deep space mission. The integration time T scales linearly with the desired number of pixels N, as $T \propto N d^{-3}$. The total integration time can be reduced if a telescope with a larger aperture is used. A larger aperture means more photons collected, reducing temporal noise such as shot noise. The diffraction pattern of a larger telescope will also be narrower, making it possible to block out more unwanted light from the solar corona.

The integration time can be greatly reduced if the exoplanet is observed only when it is partially illuminated, as the total number of illuminated image pixels is reduced. Other, regular changes due to the exoplanet's rotation and possible regular variations in its albedo may also be used to reduce the integration time further. Lastly, the performance of the coronagraph (and thus, the SNR) improves with increasing heliocentric distance[3]. These considerations yield an interesting parameter space for mission design trade-offs, which are now being investigated.

As time goes on, the same pixel may be reacquired several times, allowing for estimates of temporal variability of the target exoplanet.

3. Conclusion

By detecting numerous potential Earth-like exoplanets, the Kepler mission has raised the possibility of existence of another Earth-like world. Other exoplanet characterization technologies that are being developed currently may yield unresolved images at low spectral resolution. However, there is no concept for direct multi-pixel imaging of an exoplanet. All the exoplanet imaging concepts currently studied by NASA, aim to capture light from an unresolved Earth-like exoplanet as a single pixel. At best, these projects will provide globally averaged measurements of the exoplanet's atmosphere and may identify major biomarkers.

In contrast, a mission to the SGL is promising as it offers a means to study a previously identified exoplanet at a level of detail that is currently only possible with the solar system planets (e.g., studying surface formations to evaluate the geologic evolution of the planet). In addition, a spatially resolved spectroscopic image would allow us to probe small structures and detect weak features that would be lost in a global average (e.g., surface volcanism, land/water interactions, spatially limited biosignatures). Also, the SGL offers the opportunity to make a direct detection of life, as opposed to the indirect detection from a globally averaged spectroscopic biomarkers.

Once we find Earth-like planets with biosignatures, a spatially resolved spectroscopic observation is the imperative next step and the easiest path to what may be a mission to the SGL. Putting the optical properties of the Sun's gravitational field to use may allow exploration of a selected exoplanet decades, if not centuries, earlier than possible with other existing or foreseeable technologies.

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