Astro2020 Science White Paper

Direct Multi-Pixel Imaging and Spatially-Resolved Spectroscopy of a Potentially Habitable Exoplanet with the Solar Gravitational Lens

Thematic Areas: ☒ Planetary Systems ☐ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract:

Direct high-resolution investigations of a potentially habitable exoplanet may result in finding extra-terrestrial life, arguably the raison d'etre of space exploration. This can be achieved, if a modest astronomical telescope is delivered to the focal region of the Solar Gravitational Lens (SGL), some 650 AU from the Sun. Given the current state of space flight technologies, this can be done in ~25 years. The payoff from such a novel space-based facility would be enormous: it is the only practical way to achieve a multi-pixel image at a kilometers-scale resolution on the surface of a potentially habitable exoplanet. Instrument requirements are a telescope, a coronagraph and a spectrometer. Although programmatically, exoplanet science resides in the NASA's Astrophysics Division, an SGL imaging mission addresses the science objectives of three Divisions including Astrophysics (science), Heliophysics (flying through the Interstellar Medium) and Planetary (deep space flight with multi-year observations of a dedicated target, analogous to a planetary orbiter), which would be a major benefit to multiple science technology programs at NASA. See conceptual video description at https://youtu.be/Hjaj-Ig9jBs

1 Introduction

Direct detection of light from an Earth-like exoplanet in a habitable zone is a challenging task. The angular size of this object and its brightness are very tiny, requiring extremely large apertures or interferometric baselines. The light contamination from the parent star necessitates using advanced coronagraphic techniques. The light received from the exoplanet is exceedingly faint and rides on a noisy background. Detecting such a signal requires stable pointing and very long integration times. These challenges make direct high-resolution imaging of an exoplanet with a conventional telescope or interferometer a very difficult, if not impossible task.

Fortunately, nature has presented us with a powerful instrument that can be used for imaging. This instrument is the Solar Gravitational Lens (SGL), which takes advantage of the natural ability of our Sun's gravitational field to focus and greatly amplify light – by a factor of 100 billion – from faint, distant sources of significant scientific interest, such as a habitable exoplanet.

According to Einstein's general theory of relativity, the gravitational field induces the refractive properties of a space-time so that light rays no longer move along straight lines. A massive object acts as a lens, bending the trajectories of incident photons (Turyshev & Toth, 2017). As a result, gravitationally refracted rays of light passing on two sides of the lensing mass converge. As the bending angle is inversely proportional to the impact parameter of the light ray with respect to the lensing mass, such a lens produces not a single focal point but a semi-infinite focal line.

Although all the solar system's bodies act as lenses, only the Sun is massive and compact enough for the focus of its gravitational deflection to be within the range of a realistic mission. Its focal line is broadly defined as the area beyond ~547.8 AU, on the line connecting the center of an exoplanet and that of the Sun. A probe positioned beyond this heliocentric distance could use the SGL to magnify light from distant objects on the opposite side of the Sun (Eshleman, 1979).

While all currently envisioned NASA exoplanetary concepts would be lucky to obtain a single-pixel image of an exoplanet, a mission to the focal area of the SGL, carrying a modest telescope and coronagraph, opens up the possibility for *direct* imaging with $10^3 \times 10^3$ pixels and high-resolution spectroscopy of an Earth-like planet. Thus, an exoplanet at a distance of 30 parsecs (pc) may be imaged with a resolution of ~10 km on its surface, enough to see its surface features and potentially signs of habitability. This is depicted in a video (DeLuca, 2017).

The remarkable optical properties of the SGL include major brightness amplification ($\sim 10^{11}$ for $\lambda = 1$ μm) and extreme angular resolution ($\sim 10^{-10}$ arcsec) within a narrow field of view (Turyshev & Toth, 2017, 2019). A modest telescope at the SGL could be used for direct imaging of an exoplanet. The entire 13,000 km image of such an exo-Earth is projected by the SGL into a cylindrical volume with a diameter of ~1.3 km surrounding the focal line. Moving outwards while staying within this volume, the telescope will take photometric data of the Einstein ring around the Sun, formed by the light from the exoplanet. The collected data will be processed to reconstruct the desirable high-resolution image and other relevant information.

Recently, we have evaluated the feasibility of the SGL for direct multipixel imaging of an exoplanet (Turyshev et al., 2018). While several practical constraints have been identified, no fundamental limitations appear either with the concept or the required technologies. The investigation analyzed the requirements on operating a spacecraft at such enormous distances with the needed precision. Specifically, we studied i) how a space mission to the focal region of the SGL may conduct high-resolution direct imaging and spectroscopy of an exoplanet by detecting, tracking, and investigating the Einstein ring around the Sun, and ii) how such an approach could be used to detect the presence of life on an exoplanet. Most importantly, we determined that the foundational technologies already exist, and their development is already underway.

2 Technical Description

Theory: A wave-theoretical description of the SGL (Turyshev & Toth, 2017) demonstrates that it possesses a set of rather remarkable optical properties. Specifically, the SGL amplifies the brightness of light from distant, faint sources by a factor of $\sim 2GM/(c^2\lambda) \sim 10^{11}$ (for $\lambda = 1$ μm), which is an enormous magnifying power not easily achievable with conventional astronomical instruments. The SGL has extreme angular resolution of $\lambda/D_0 \sim 10^{-10}$ arcseconds (with D_0 being the diameter of the Sun), which makes it exceptionally well-suited for imaging distant objects.

The angular diameter of an Earth-like exoplanet at 30 pc is 1.4×10^{-11} rad. To resolve the disk of this planet as a single pixel, a telescope array with a baseline of ~74.6 km would be needed. Resolving the planet with 10^3 linear pixels would require a baseline $\sim 1\times 10^5$ km ($\sim 12R_\oplus$), which is not feasible.

In contrast, a 1-m telescope, placed at the focal line of the SGL at 750 AU from the Sun, has a collecting area equivalent to a diffraction-limited telescope with diameter of ~90 km and the angular resolution of an optical interferometer with a baseline of $12R_\oplus$. While building an instument with the SGL's capabilities is far beyond our technological reach, we can use the SGL's unique capabilities to capture megapixel images of exoplanets.

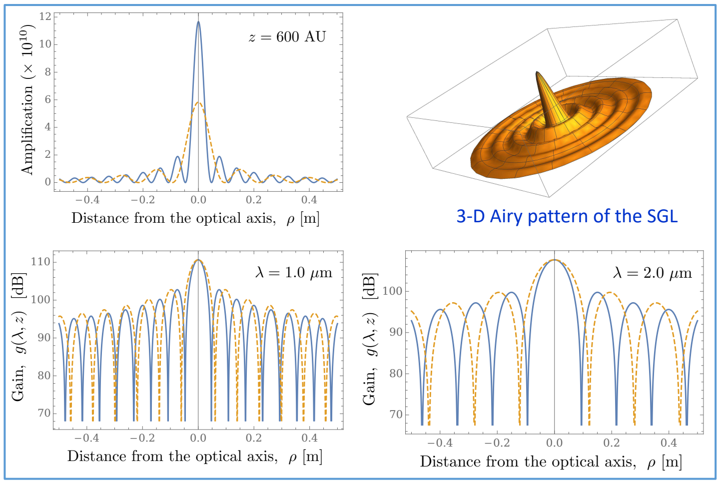

Figure 1. Optical properties of the SGL (Turyshev & Toth, 2017). Up-Left: Amplification of the SGL. Up-Right: Point spread function. Bottom: Gain of the SGL as seen in the image plane as a function of possible observational wavelength.

Recent efforts have produced a better understanding of the optical properties of the SGL. Figure 1 shows the lens' point-spread function (PSF), resolution, magnification, all of which helps in the design of the large-scale astronomical facility that would benefit from the SGL.

Imaging concept: The image of an exo-Earth, for instance at 30 pc, is compressed by the SGL to a cylinder with a diameter of ~1.3 km (corresponding to the Einstein ring around the Sun with the same 1.3 km thickness) in the immediate vicinity of the fictitious focal line. Imaging an exo-Earth with $10^3 \times 10^3$ pixels requires moving the spacecraft within the image plane in steps of 1.3 km /10^3 ~ 1.3 m while staying within the ~1.3 km diameter cylindrical volume. So, each ~1 m pixel in the image plane corresponds to a pixel diameter of ~10 km on the surface of the planet.

The challenge comes from the fact that the PSF of the SGL is quite broad (see Figure 1), falling off much slower than the PSF of a typical lens. Consequently, for any pixel in the image plane, this leads to combining light not just from a particular pixel on the surface of the exoplanet but also from many adjacent pixels. This leads to a significant blurring of the image.

To overcome this impediment, imaging must be done on a pixel-by-pixel basis by measuring the brightness of the Einstein ring at each of the image pixels. The knowledge of the PSF's properties makes it possible to apply deconvolution algorithms that enable reconstruction of the original image efficiently. To make this process work, a significant signal to noise ratio (SNR) is required. Fortunately, the SGL light amplification capability provides a SNR of over 10^3 given a 1 second of integration time. This is sufficient for nearly noiseless deconvolution (Turyshev et al., 2018).

Light contamination from the parent star is a major problem for all modern planet-hunting concepts. However, for the SGL, due to its ultrahigh angular resolution (~10^{-10} arcsec) and very narrow FOV, the parent star is completely resolved from the planet with its light amplified ~10^4 km away from the planet's optical axis, making the parent star contamination issue negligible.

Instrument: Thanks to the large photometric gain of the SGL, its high angular resolution and strong spectroscopic SNR (10^3 in 1 sec), a small diffraction-limited high-resolution spectrograph is sufficient for the unambiguous detection of life (Turyshev et al., 2018).

As the instrument ultimately determines the size of the spacecraft, recently we addressed the issues of coronagraph design. For this, we require the coronagraph to block solar light to the level of the solar corona brightness at the location of the Einstein ring.

At 1 μm, the light amplification of the SGL is ~2×10^{11} (equivalent to −28.2 mag), so an exoplanet, which initially is seen as an object of 32.4 mag now becomes a ~4.2 mag object. When averaged over a 1-m telescope, light amplification is reduced to ~2×10^9 (−23.25 mag), the exoplanet becomes a 9.2 mag object, still sufficiently bright. However, the image will include noise in the form of light from the solar corona, the residual solar light, and the zodiacal light.

To validate our design assumptions, we performed a preliminary coronagraph design and simulations. Suppressing the Sun's light by a factor of 10^{-6} when imaging with the SGL is significantly less demanding than the requirements for modern-day exoplanet coronagraphs, which must suppress the parent star's light by a factor of 10^{-10} to detect an exo-Earth at least as a single pixel.

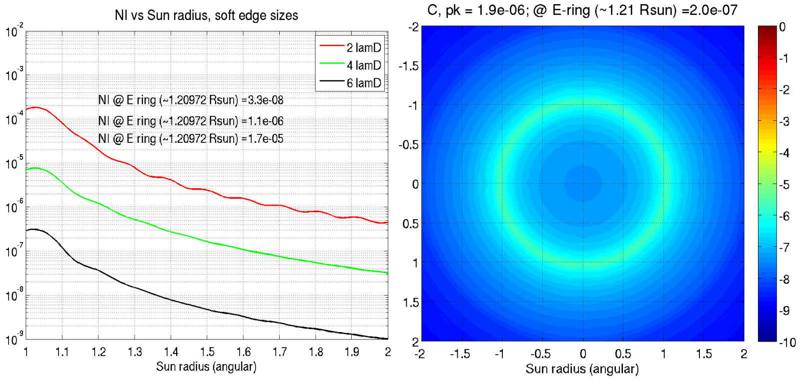

Figure 2. Left: Gaussian soft-edge has a great impact on light suppression ability of the coronagraph. Right: Simulated coronagraph performance showing the solar light suppression by 2×10^{-7}, sufficient for SGL imaging.

We evaluated the performance of the coronagraph with a Fourier-based diffraction model. The Sun is modelled as a dense collection of incoherent point sources with its corona at the relevant heliocentric ranges obeying ~r^{-3} power law profile. Design parameters include telescope size, distance to the SGL, occulter mask profile and Lyot mask size. The full width at half maximum of the Gaussian soft edge has a significant impact on the coronagraph's performance (Figure 2).

Defining contrast as brightness normalized to peak brightness without coronagraph, we achieved a total planet throughput of ~10%. Figure 2 shows the contrast at the image plane after the coronagraph. At a contrast of 2×10^{-7}, the leaked solar light is ~5 times lower in intensity than the corona, satisfying the stated objectives for imaging with the SGL (Turyshev et al., 2018).

Image Reconstruction: Creating a megapixel image requires ~10^6 separate measurements. For typical CCD photography, each detector pixel within the camera is performing a separate measurement. This is not the case for the SGL. Only the pixels in the telescope detector that image the Einstein ring measure the exoplanet, and the ring contains information from the entire exoplanet, due to the disproportional image blurring by the SGL and also due to the relative distribution of different regions of the exoplanet to different azimuths of the ring. The rotational deconvolution yields a super resolution that allows us to see a major part of the surface of the exo-Earth in a few months of integration time; it would also allow us to peak under the cloud cover.

With direct deconvolution on a 1-m telescope, it would take ~1.2 years to build a 500 × 500-pixel image of the entire planet. This time is needed to remove the contribution of the solar corona that is not taken out by the coronograph. Two factors that can reduce the integration time by a factor of up to 100 are i) the number of image pixels, N, and ii) the telescope diameter. The higher the desirable resolution the longer is the integration time, T, scaling as $T \sim N D^4$, where D is the distance to the target. Another scaling law is related to the telescope diameter, d. A telescope with double the aperture will collect four times as many photons. Its diffraction pattern will be twice as narrow and, thus, it will collect half as many solar corona photons. The integration time scales as $T \sim d^{-3}$. Thus, a larger image of $10^3 \times 10^3$ pixels may be produced in ~3.4 years if a 2-m telescope is used. However, T may be reduced if there are time-varying features in the planetary albedo (regular features and/or cloud pattern, etc.). The time is also reduced by $\sim n^{-1}$ if n imaging spacecraft are used. Other factors are i) the rotational motion of a crescent exo-Earth, and ii) increase in heliocentric distance and the resulting improvements in coronagraphic performance.

Turyshev et al. (2018) have shown that imaging with the SGL, although complex, has no fundamental "show-stoppers." Given the enormous light amplification provided by the SGL, spectroscopic investigations, even spectro-polarimetry could be viable. Ultimately, one could obtain not just an image, but a spectrally-resolved image over a broad range of wavelengths, characterizing the atmosphere, surface materials and biological processes on that exo-Earth.

Our analysis suggests that with all the effects taken into account, including scattering of light by the ever-present interstellar dust, we could collect enough light in approximately half a year to form the first ever direct megapixel-class-resolution image of an exoplanet. As nothing is stationary in the universe – the planet orbits its own star which also moves with respect to our own sun -– the spacecraft must have the propulsion system that would be used to compensate for such a motion. If we were limited to conventional imaging by a giant unitary telescope or by multiple telescopes arrayed for interferometry, the telescope or telescopes would have to stare for millions of years to gather enough light. An SGL-aided imaging facility could do this job with a year.

3 Potential approach for science implementation

Direct investigations of exoplanets with the SGL is within both astrophysics (exoplanet science) and planetary (similar to a planetary orbiter to a chosen target.) Observing the identified exoplanet begins at ~650 AU and then requires flying outward along the focal line. To do this in <30 years requires traveling nearly 8 times faster than Voyager. In addition, to assemble the parts of a unitary image from the pixels in the Einstein ring, the spacecraft will have to maneuver small distances around the focal line. It also will have to compensate for the orbital motion of the target planet and the barycentric motion of the Sun. As hard as those tasks are, they are $\sim 10^3$ (if not 10^6) times easier than competing approaches to closely observe an exoplanet, which would involve the huge (and enormously expensive) task of building kilometer sized telescopes in space. Fortunately, all the technologies required for a mission to the SGL are already either in development or operational.

Possible propulsion for a SGLF mission includes nuclear electric or nuclear thermal, both resulting in very large spacecraft at very high cost. Solar thermal is being studied but it requires a huge thermal shield to fly within 2 to 3 solar radii of the sun for a gravity assist that would accelerate it enough to exit the solar system. Chemical propulsion cannot provide adequate velocity, even with such a close solar flyby. The solar thermal approach is new, and it deserves further study. A promising and certainly more affordable approach is to use solar sails with a small spacecraft – using the rapidly evolving technology of smallsats. A smallsat with a mass of, say, 50 kg, and a solar sail measuring 200 x 200 meters, could achieve exit velocities approaching 25 AU/year, depending on the sail material and how close it can get to the Sun (Friedman, Garber. 2014). We currently consider 0.1 AU (21 solar radii) a reasonable goal for the solar sail spacecraft. In addition to providing a much lower cost, this approach also provides a replicable one permitting us to consider launching multiple spacecraft to observe multiple targets or to arranging telescopes in distributed architectures that increase reliability, redundancy and mission design flexibility.

The size of the smallsat will be dictated by the required telescope size (e.g. 1-2 meters) and the radioisotope power system requirements. The power system will supply the energy for electric "micro-thrusters" to enable maneuvering around the focal line as the spacecraft flies outward beyond 650 AU. It will have months and years to observe the target exoplanet, deconvolute the image, and communicate to Earth – a virtual orbiter of the distant exoplanet. Clearly, the SGL imaging concept enables a significant flexibility in the exoplanet remote sensing science campaign.

It will also be possible to observe entire planetary systems, several exoplanets, orbiting the same star since their focal lines will be relatively close. This makes the SGL-enabled imaging concept similar to the missions currently conducted by the solar system planetary community.

4 Towards a high-resolution image of an exoplanet

Exoplanet discovery has burgeoned. Kepler has identified many potentially habitable worlds, and more is expected from TESS, JWST, other follow-ups. There are also missions yet in formative stages, such as the Exo-C, Exo-S, HabEx, LUVOIR concepts (Turyshev et al, 2018).

However, there is no concept for direct multi-pixel imaging of an exoplanet. All the exoplanet imaging concepts currently available, aim to capture light from an Earth-like exoplanet as a single pixel. These missions would provide globally averaged measurements of the atmosphere, identify major biomarkers, etc. However, SGL will open scientific questions to the exoplanet community that are currently only open to planetary scientists in the solar system (e.g., studying surface landforms to evaluate the geologic evolution of the planet). In addition, a spatially resolved spectroscopic image allows 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 provides the opportunity to make a direct detection of life, as opposed to the indirect detection from a globally averaged spectroscopic biomarker.

This work is of major interdisciplinary importance. Just getting out to the SGL provides lots of collaborations with heliophysics and astrophysics (Stone et al., 2015). Also, there is more direct interdisciplinary nature of planetary scientists and exoplanet scientists. Although this connection is growing, there is still a major chasm between the rich observations that planetary scientists use versus the few globally averaged parameters that astronomers are using with exoplanets.

A mission to the SGL is a new mission concept, with enormous scientific potential, but technical issues involving propulsion, communication, autonomy still must be resolved (Turyshev et al., 2018). However, if and when we find Earth-like planets with biosignatures, a spatially resolved spectroscopic observation is THE imperative next step and the easiest path to that is the SGL. That could happen sooner than we expect.

Therefore, we ask the NAS Decadal Committee to endorse a study of mission and system concepts capable of exploiting the remarkable optical properties of the SGL for *direct* high-resolution imaging/spectroscopy. Such missions could allow exploration of exoplanets relying on the SGL decades, if not centuries, earlier than possible with other extant technologies. We would need to conduct a system study of the mission concept including imaging, propulsion, CONOPS, and smallsats. The latter would enable lower cost, affordable mission concepts, potentially even of New Frontier class. The study will focus on the feasibility of the SGL mission with the aim of life detection, multi-pixel, kilometers scale direct imaging of a potentially habitable exoplanet.

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References:

Eshleman, V.R., *Gravitational Lens of the Sun: Its Potential for Observations and Communications over Interstellar Distances*, Science 205, 1133 (1979);

DeLuca, J., *Exoplanet imaging with the solar gravitational lens*, (2017), see at: https://www.youtube.com/watch?v=Hjaj-Ig9jBs;

Friedman, L. and Garber D., *Science and Technology Steps into the Interstellar Medium,* IAC 14, D4,4,3,x22407, International Astronautical Congress (2014);

Turyshev, S.G., and V.T. Toth, *Diffraction of light by the solar gravitational lens: a wave-theoretical treatment*, Phys. Rev. D 96, 024008 (2017), arXiv:1704.06824 [gr-qc];

Turyshev, S.G., and V.T. Toth, *Diffraction of light by the gravitational field of the Sun and the solar corona*, Phys. Rev. D 99, 024044 (2019), arXiv:1810.06627 [gr-qc];

Turyshev, Slava G., Michael Shao, Leon Alkalai, Nitin Aurora, Darren Garber, Henry Helvajian, Tom Heinsheimer, Siegfried Janson, Jared R. Males, Dmitri Mawet, Roy Nakagawa, Seth Redfield, Janice Shen, Nathan Strange, Mark R. Swain, Viktor T. Toth, Phil A. Willems, John L. West, Stacy Weinstein-Weiss, Hanying Zhou, *Direct Multipixel Imaging & Spectroscopy of an exoplanet with a Solar Gravity Lens Mission*, The Final Report: A NASA Innovative Advanced Concepts (NIAC) Phase I grant (2018), arXiv:1802.08421 [gr-qc];

Stone, E., et al., (2015), The KISS Final Report on *Interstellar Precursors*: http://kiss.caltech.edu/final_reports/ISM_final_report.pdf