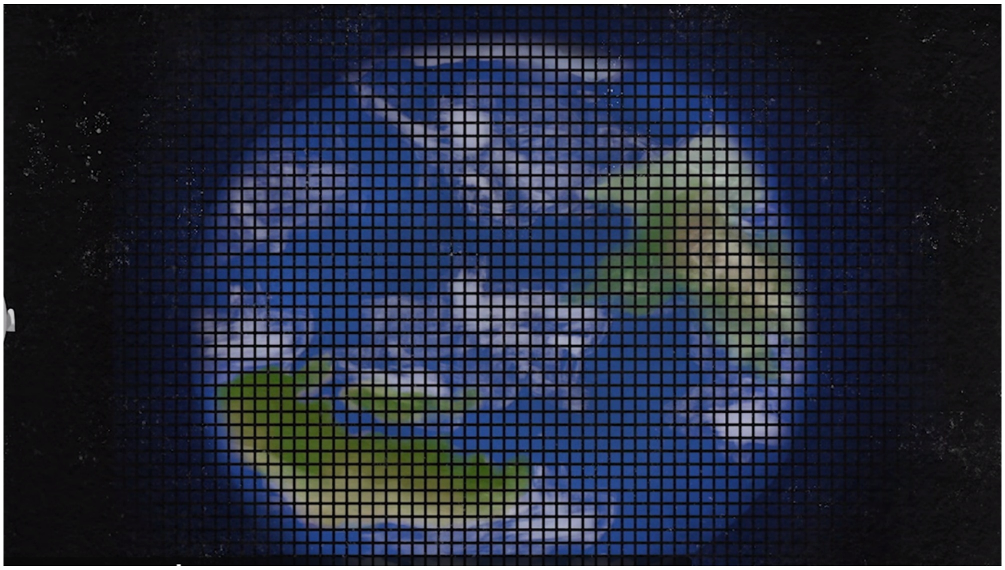
A Mission to Find and Study Life on an Exoplanet

Using the Solar Gravity Lens to Obtain Direct Megapixel Imaging of a Putative Habitable World and High-Resolution Spectroscopy of its Atmosphere

Response to A Call for White Papers
"Astrobiology Science Strategy for the Search for Life in the Universe"

Slava G. Turyshev[1], Michael Shao[1], and Louis Friedman[2]
[1]*Jet Propulsion Laboratory, California Institute of Technology,*
4800 Oak Grove Drive, Pasadena, CA 91109-0899, USA
[2]*The Planetary Society, Emeritus, http://www.planetary.org/*



A 1-meter telescope with a coronagraph (with 10^{-6} suppression) placed in the focal area of the solar gravitational lens (SGL) can image an exoplanet at the distance up to 100 light years with a kilometer-scale resolution on its surface. In addition, spectroscopic broadband signal-to-noise ratio is ~10^6 in 2 weeks of integration time, providing this instrument with incredible remote-sensing capabilities. See concept description at https://www.youtube.com/watch?v=Hjaj-Ig9jBs

Contact information:
Dr. Slava G. Turyshev
Jet Propulsion Laboratory, MS 169-237
4800 Oak Grove Drive, Pasadena, CA 91109 USA
v: +1(818)393-2600 e: turyshev@jpl.nasa.gov
http://science.jpl.nasa.gov/people/Turyshev/

December 2017

A Mission to Find and Study Life on an Exoplanet

A White Paper for the NAS Space Science Board

Slava G. Turyshev[1], Michael Shao[1], and Louis Friedman[2]
[1]Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA 91109-0899, USA
[2]The Planetary Society, Emeritus, http://www.planetary.org/

Finding life on another world is perhaps the principal goal of space exploration, both for the public funding such exploration and for the scientists seeking to understand the questions of life in the Universe. Numerous apparently habitable worlds, potential abodes of life, have now been discovered around other stars, and many more can be expected to be discovered in the next few years. It is almost certain that a tantalizing hint of life on one or more worlds will be obtained. But, only a hint – to determine life will require either going to those other worlds or remotely studying them in detail over a long period of time. Both are beyond our present capability.

Going there (perhaps tens of light-years from Earth) will remain impossible, if not forever, certainly for a long time. Detailed remote study is only possible with very large telescopes, tens of kilometers, at very high cost, or by using the very high magnification and angular resolution provided to us by nature – the solar gravity lens (SGL). The SGL results from the natural phenomenon of the large gravitational field of the Sun to 'bend' and focus light from a distant object, e.g. an exoplanet. The focus is a line – along which a spacecraft could fly for years to make repeated high-resolution observations. In the foreseeable future, a small-sized telescope (1-2 m) could operate on the focal line of the SGL at distances between 600 – 900 AU from the Sun, to provide kilometer (km) scale direct images of a distant exoplanet. This instrument could deliver ($10^3\times10^3$)-pixel images of "Earth 2.0" at distances of up to 100 light years (ly) and with a spatial resolution of ~10 km on its surface, enough to see its surface features with signatures of life.

According to Einstein's general relativity, gravity imparts refractive properties on space-time causing a massive object to act as a lens by bending photon trajectories. As a result, for a given solar impact parameter, the gravitationally deflected rays of light passing from all sides of the lensing mass converge at a focus, as shown in Fig. 1. Gravitational lensing is a well-known effect and has been observed over cosmological distances where relatively nearby galaxies, or even clusters of galaxies, act as gravitational lenses for background galaxies, and even in our Galaxy where micro-lensing of stars in the Galactic bulge or in the Magellanic clouds are caused by intervening (sub-)stellar bodies. In our Solar System, this effect was originally observed by Eddington in 1919 (thus confirming formally Einstein's theory) and now is routinely accounted for in astronomical observations and deep space navigation (Turyshev 2008).

Of the solar system bodies, only the Sun is massive enough that the focus of its gravitational deflection is within a range of a realistic mission. Depending on the impact parameter, the focus of the SGL is a semi-infinite line that begins at ~547AU. The "focal line" (FL) of the SGL is broadly defined as the area beyond 547AU from the Sun on the line that connects the center of an exoplanet and the center of the Sun. By naturally focusing light from a distant source (Eshleman 1979; Turyshev & Andersson 2003), the SGL provides brightness amplification (~10^{11} at λ=1 μm) and extreme angular resolution (~10^{-10} arcsec) in a narrow FOV (Turyshev 2017; Turyshev & Toth, 2017). The entire image of an exoplanet at 100 ly away from us is compressed by the Lens into a small region with diameter of ~1.3 km in the immediate vicinity of the focal line. In the pencil-sharp region along the focal line, the amplification and angular resolution of the SGL stay nearly constant well beyond 2,500 AU. For example, to appreciate the enormity of the magnifying power and resolution of such a system, a 1-m telescope placed on the FL of the SGL at 750 AU from the Sun has a collecting area equivalent to a telescope with diameter of ~80 km and angular resolution of an optical interferometer with a baseline of 16 Earth's radii. Such a telescope at the focal region of the SGL would provide high-resolution images and spectroscopy of a habitable exoplanet.

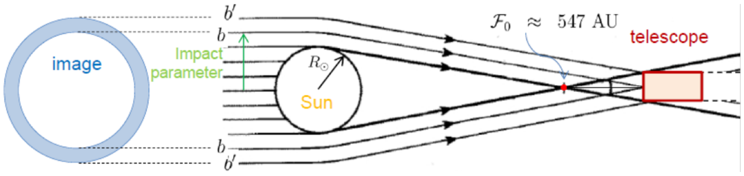


Fig. 1. Imaging of an exo-Earth with solar gravitational Lens. The exo-Earth occupies (1km×1km) area at the image plane. Using a 1m telescope as a 1 pixel detector provides a (1000×1000) pixel image.

As seen from a telescope at the FL, the light from an exoplanet occupies an annulus surrounding the edge of the Sun (Fig. 1). This light, while magnified greatly, is still much dimmer than the Sun. A modest coronagraph (~10^6 suppression) would be used to block the solar corona, so that the exoplanet's light could be detected at the telescope.

At 550 AU the Sun subtends ~3.5''; for λ=1 μm, the diffraction limited size of a 1-m telescope has a beam size of ~0.1" (or 35 times smaller; thus, no need to go beyond 1,000 AU). Majority of light in this narrow annulus comes from a ~(10 km × 10 km) spot on the exoplanet's surface. However, light outside the annulus would come from the adjacent areas on the exoplanet. This light will also be blocked by the coronagraph.

The instrument for a mission to the focal region of the SGL should implement a miniature diffraction-limited high-resolution spectrograph, enabling Doppler imaging techniques, taking full advantage of the SGL amplification and differential motions (e.g. exo-Earth rotation). Taking into account the solar corona the broadband SNR is ~10^3 in 1 sec. Thus, if we want to get SNR of 10^6, we would need 10^6 seconds (or ~2weeks). This implies that for a spectral resolution of 10^4 the SNR (in each spectral element) would be 10^4. With spectral resolution of 1 million, we would still have SNR = 10^3, again in only 2 weeks of integration. Clearly shown a significant potential for finding and studying life on an exoplanet by remote sensing its atmosphere. A coronagraph capable to satisfy the requirements for imaging with the SGL was recently designed at JPL (Shao et al. 2017). This design is able to achieve the solar light suppression of better than 10^{-7}, providing a healthy margin for the mission development. Given the rapid development of coronagraphic capabilities, we can therefore assume that direct imaging will provide spectro-photometric characterization of the exo-Earth.

Fig. 2. An image of the Earth with resolution of (10^3×10^3) pixels. To illustrate imaging capabilities of the SGL.

The image of the exo-Earth at ~100 ly would extend ~1.3 km at the location of the spacecraft on the optical axis of the SGL. The spacecraft would have to scan this (1.3 km × 1.3 km) area one pixel at a time (or consist of a constellation of several apertures) to develop a multi-pixel image of an exo-Earth with resolution of (10^3 × 10^3) pixels as shown in Fig. 2. A computer animation of a mission concept to capture images and spectroscopy of the exoplanet through the SGL was recently developed and is available on YouTube (DeLuca 2017).

Effects of the radial/azimuthal plasma density of the solar corona (Turyshev & Andersson 2003, Turyshev & Toth 2017, op.cit.) on the structure of lensing caustic were recently taken into account, including analysis of the contributions for the solar gravitational harmonics, second order effects, and chromatic structure of the caustic (Turyshev & Toth 2018). These effects result in additional aberrations that modify the caustic formed by the Sun which may be quite useful in the image reconstruction process. The additional aberrations (from higher-order gravitational harmonics of the Sun) are well-known and are easy to account during deconvolution. In fact, they provide some variability in the image that may be used to our advantage in the image reconstruction, perhaps, leading to even a higher precision of reconstructed images.

While all currently envisioned NASA exoplanetary concepts aim at getting just a single pixel to study an exoplanet, a mission to the SGL opens up a breathtaking possibility for *direct* $(10^3\times10^3)$ pixels imaging and spectroscopy of an Earth-like planet up to 100 ly with resolution of ~10 km on its surface, enough to see its surface features and signs of habitability. Such a possibility is truly unique and was never studied before in the context of a realistic mission.

The key new technologies that now enable consideration of such a mission are smallsats (spacecraft less than 100 kg with power, communications, precision control and navigation, etc.) and solar sails. One interplanetary sail has already flown to vicinity of Venus (JAXA's IKAROS) (van der Ha et. al., 2015) and another to a Near-Earth Asteroid is now being developed by NASA (NEA Scout) (McNutt et. al., 2014). While conventional propulsion (chemical) in principle could be used with a large solid rocket motor flying very close to the Sun, even with optimistic assumptions the speed of such a probe is limited to about 17 AU per year (Stone, Alkalai & Friedman, 2015). As described below a (300 x 300) meter solar sail, with a spacecraft mass of 100 kg could fly out of the solar system at ~25 AU per year, enabling reaching the SGL in a less than 25 years of flight.

Friedman & Garber (2014) first considered the SGLF as an interstellar precursor. They studied solar sail requirements to reach exit velocity speeds of over 20 AU per year. The results are summarized in Fig. 3. Garber (2017) has extended this analysis to consider the area/mass requirements to reach an exit velocity of up to 40 AU/year. His result is given in Fig. 4. Sail area to spacecraft mass ratios of 900 m^2/kg yield a speed of 25 AU/year, 30 AU/year requires A/m=1400 and 40 AU/year requires A/m= 2550.

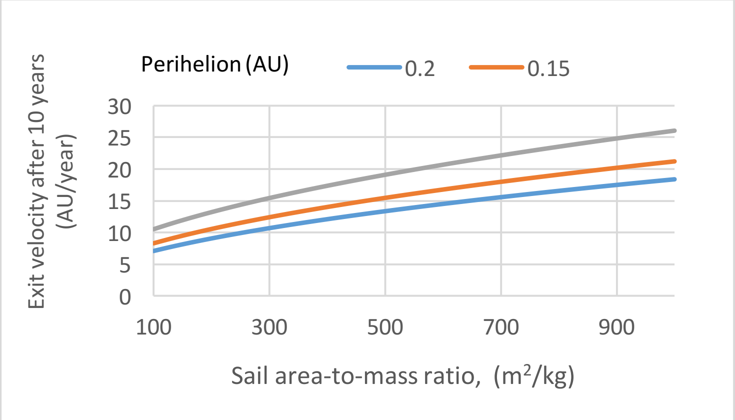


Figure 3: A solar sail spacecraft exit velocity from the solar system vs. sail area to spacecraft mass ratio and perihelion distance.

Since any spacecraft will need power – presumably a small radioisotope generator, we consider that radioisotope electric power (REP) thrusters can provide an additional boost to the solar sail spacecraft as well as propulsion for in-space maneuvers, such as midcourse navigation and maneuvers in the Einstein Ring to collect the image pixels. A JPL study (Liewer et al. 2000; Mewaldt & Liewer 2000) cited an Advanced Radioisotope Power System delivering 106 W weighing 8.5 kg (~12.5 W/kg). A system this small would be insufficient for boosting spacecraft velocity but might provide enough propulsion for small maneuvers and attitude control. Quantitative studies need to be done in a system design. The REP might boost the velocity by as much as 20%, e.g. 5 AU/year -- albeit, likely with a heavier system.

When we reach the focus of the SGL, we must continue to fly along the focal line for a flight time as long as it took us to get there, e.g. another 25 years. Images of the exo-planet will have to be constructed through a complicated de-convolution process of pixels sampled in the Einstein ring around the FL (see Fig.1). That is the spacecraft will have to sample the image of an exo-Earth with the diameter of 1.3 km around the FL while travelling at speeds ~25 AU/year. Tethering or electric propulsion could be used to perform raster-scanning with a spacecraft located >550 AU away. For an exo-Earth 100 ly away, the planet's image moves in a 45,000-km diameter 1-year orbit. Its image at the focus of the SGL is ~1.3 km in diameter. One way to scan the image of an exo-Earth is to conduct a spiral scan to follow the planetary motion while using a ~1.3-km tether and the RTG on the other end of it (to balance the spacecraft). This reduces the fuel requirement for raster scanning the image.

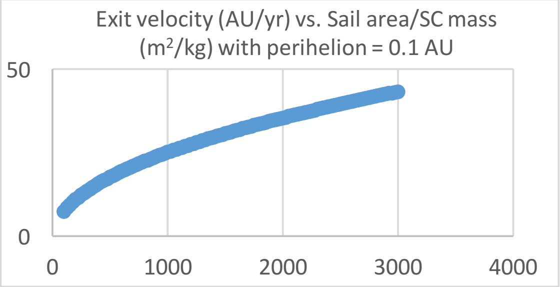


Figure 4 Exit velocity as a function of sail area/mass ratio.

Conclusion

Ever since Galileo invented a telescope, astronomical telescope making has been an evolving discipline. The task of designing of a modern telescope is complex, involving consideration of materials, detectors, precision manufacturing, tools for optical and thermal analysis, and etc. The largest telescope so far is the European Extremely Large Telescope (ELT) with aperture of 39.3 m that is currently under construction in Chile. A telescope with diameter of tens of kilometers in space to get a megapixel scale direct image of an alien world is beyond our technological reach. The SGL holds the promises of providing us with such cosmic capabilities.

It remains to be determined just how complex will be the capturing and creation of direct images of an exo-planet using the SGL. It also remains to be determined what would be the cost of a mission to its focal region. However, if it does prove to be a feasible mission, there may be cost and science tradeoff between remote sensing using the solar gravity lens and flying to, operating and returning data from a planet in another star system many light years away. In any case, the first job is to simulate creating the image in the SGLF. This is being done in a current NIAC study (Turyshev et al., 2017). Although we investigate the question of spacecraft design of how to reach the extremely large regions outside the solar system, the primary emphasis is placed on the feasibility of mission operations in support of the primary science objectives – the high-resolution imaging and spectroscopy.

The SGL offers a unique means for imaging exo-planets and determining their habitability. A complete set of requirements to use it to create such an image remain to be determined. A comprehensive study of a Solar Gravity Lens Focus mission is needed. Theoretical considerations are promising, both for getting there and for capturing high resolution images and spectra of potentially habitable exo-planet. The mission has the potential of being the most (and perhaps only) practical and cost-effective way of obtaining kilometer scale resolution of a habitable exoplanet, discovering, and studying life on other worlds.

Concluding, we suggest that it is time to initiate a study of a mission to the deep regions outside the solar system that will exploit the remarkable optical properties of the SGL to effectively build an astronomical telescope capable of direct megapixel high-resolution imaging and spectroscopy of a potentially habitable exoplanet. Although theoretically seem feasible, the engineering aspects of building such an astronomical telescope on the large scales involved were not addressed before. There are many unique and exciting features of such a mission to the SGL that warrant such a study in the near time, perhaps even at the beginning of the next decade.

References:

DeLuca, J., "Exoplanet imaging with the solar gravitational lens," 2017, animation, see at YouTube at: https://www.youtube.com/watch?v=Hjaj-Ig9jBs

Eshleman, V. R., "Gravitational Lens of the Sun: Its Potential for Observations and Communications over Interstellar Distances," Science 205, 1133—1135 (1979).

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

Garber, D., private communication (2017).

McNutt, L., Johnson, L., Kahn, P., Castillo-Rogez, J., and Frick, A., "Near-Earth Asteroid (NEA) Scout," AIAA SPACE 2014 Conference and Exposition, AIAA SPACE Forum, (AIAA 2014-4435).

Liewer, P. C., Mewaldt, R. A., Ayon, J. A., and Wallace, R. A., "NASA's Interstellar Probe Mission", in Space Technology and Application International Forum-2000, edited by M. S. El-Genk, AIP Conference Proceedings CP504, American Institute of Physics, New York, p. 911 (2000)

Mewaldt, R. A., Liewer, P. C., "An Interstellar Probe Mission to the Boundaries of the Helisosphere and Interplanetary Space," AIAA Space Forum (2000), https://interstellar.jpl.nasa.gov/interstellar/ISP_Space2K_v4.pdf

Shao, M., Zhou, H., Turyshev, S. G. "Design for the SGL Extended Source Coronagraph," JPL, unpublished (2017).

Stone, E., Alkalai, L., Friedman, L., "Science and Technology for Exploring the Interstellar Medium", Keck Institute for Space Studies Report, 2015, http://kiss.caltech.edu/workshops/ism/ism.html

Turyshev, S. G., Andersson, B-G, "The 550 AU Mission: A Critical Discussion," MNRAS 341 (2003) 577-582, gr-qc/0205126.

Turyshev, S. G., "Experimental Tests of General Relativity," Annu. Rev. Nucl. Part. Sci. 58, 207-248 (2008), arXiv:0806.1731 [gr-qc].

Turyshev, S. G., Shao, M., Mawet, D., Strange, N., Swain, M., Alkalai, L., and Males, J. "Direct Multipixel Imaging and Spectroscopy of an exoplanet with a Solar Gravity Lens Mission," A NASA Innovative Advanced Concepts (NIAC) Phase I proposal (2017), see at https://www.nasa.gov/directorates/spacetech/niac/2017_Phase_I_Phase_II

Turyshev, S. G., "Wave-theoretical description of the solar gravitational lens," Phys. Rev. D 95, 084041 (2017), arXiv:1703.05783 [gr-qc]

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

Turyshev, S. G., and Toth, V., "Scattering of light by the gravitational field of the Sun and the solar corona," Phys. Rev. D, to be submitted (2018).

Van der Ha, J., Mimasu, Y., Tsuda, Y., and Mori, O. "Solar and Thermal Radiation Models and Flight Evaluation for IKAROS Solar Sail", J Spacecraft & Rockets 52 (3) (2015), pp. 958-967.