Astro2020 Science White Paper

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

Thematic Areas: ☒ Planetary Systems ☒ APC white paper

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Abstract:

Direct high-resolution investigations of a potentially habitable exoplanet may result in finding the signs of extraterrestrial life, arguably the *raison d'être* of space exploration. This can be achieved with a modest astronomical telescope, delivered to the focal region of the Solar Gravitational Lens (SGL) some 650 AU from the Sun. Given the current state of spaceflight technologies, this can be accomplished with a flight time of ~25 years. The payoff from such a truly unique space-based facility would be enormous. It is the only practical way to obtain a multipixel image of the surface of a potentially habitable exoplanet at a kilometer-scale resolution. Instruments required are a small telescope with a coronagraph and a spectrometer. A modest-cost (i.e., New Frontiers class) multi-smallsat spacecraft approach is being studied for the mission implementation – one that may enable a practical way to accomplish the mission sooner than would otherwise be expected. 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 multiyear observations of a dedicated target, analogous to a planetary orbiter), which would be a major benefit to multiple science and technology programs at NASA. See conceptual video description at https://youtu.be/Hjaj-Ig9jBs

1 Introduction: *Key Science Goals and Objectives*

Direct detection of light from an Earth-like exoplanet in a habitable zone is a challenging task. The angular size of such an object is very tiny and it is very dim, requiring extremely large apertures or interferometric baselines. Light contamination from the parent star necessitates the use of advanced coronagraphic techniques. Light received from the exoplanet is exceedingly faint, on a noisy background. Detecting such a signal requires stable pointing and very long integration times. To capture a single-pixel image of an Earth-like exoplanet at 30 parsec (pc), a diffraction-limited telescope would require an aperture of ~90 km. Optical interferometers with telescopes of moderate size and large baselines would require integration times of hundreds of thousands if not millions of years to get a reasonable signal-to-noise ratio (SNR). Clearly, these scenarios are impractical, making direct high-resolution imaging of an exoplanet with a conventional telescope or interferometer a very difficult, if not impossible task.

These challenges lead us to examine other ways to obtain high-resolution, multipixel images of distant, small and dim targets. After an extensive and still ongoing study (Turyshev et al., 2018), we concluded that the solar gravitational lens (SGL) is the only practical means to accomplish this exciting objective. The SGL takes advantage of the natural ability of our Sun's gravitational field to focus and greatly amplify light – up to a factor of 100 billion – from faint, distant sources of significant scientific interest, such as habitable exoplanets.

According to Einstein's general theory of relativity, gravitation induces refractive properties on spacetime, so that light rays no longer follow straight lines. A massive object acts as a lens, bending photon trajectories (Turyshev & Toth, 2017). As a result, gravitationally refracted rays of light passing on two sides of the lensing mass converge. The Sun is massive and compact enough for the focus of its deflection to be within reach of a realistic mission. Its focal area begins at ~547.8 AU (see Figure 1), on the line connecting the center of an exoplanet and that of the Sun. The SGL does not have a single focal point. Rays with a larger impact parameter focus at a greater distance from the Sun, forming a focal half-line. A probe positioned on this focal line could use the SGL to amplify light from faint objects on the opposite side of the Sun (Eshleman, 1979).

The remarkable optical properties of the SGL include major brightness amplification (~10^{11} for $\lambda = 1$ μm) and extreme angular resolution (~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. With a compression factor of (distance to the probe)/(distance to the exoplanet) ~10^{-4}, the entire ~1.3×10^4 km image of an exo-Earth at 30 pc 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.

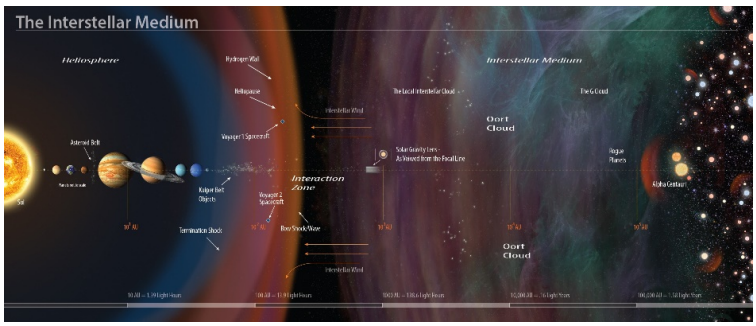

Figure 1. The SGL's focal area begins at 547.8 AU or 4 light days out.

The large heliocentric distances separating us from the beginning of the SGL focal region were previously hard to contemplate. But the success of Voyager 1, now more than 145 AU from the Sun (see Figure 1) while still transmitting data, combined with

multiple recent developments in deep space exploration technologies, a mission beyond 550 AU appears more within reach. This allows us to consider practical applications of the SGL as an optical instrument that could be used for multipixel imaging and spatially resolved spectroscopy of an exoplanet (Turyshev et al., 2018).

Currently envisioned NASA exoplanetary concepts would be lucky to obtain a single-pixel image of an exoplanet. In contrast, a mission to the focal area of the SGL, carrying a modest telescope and coronagraph, opens up the possibility for *direct* imaging with 1,000 × 1,000 pixels and high-resolution spectroscopy of an Earth-like planet. An exoplanet at a distance of 30 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). Our ***key objective***, therefore, is to study a mission to the SGL to perform direct multipixel imaging and spatially resolved spectroscopy of a potentially habitable exoplanet. We understand that development of such a mission takes time. We argue that now is the time to begin this effort.

Recently, under a 3-year grant from the NASA Innovative Advance Concepts (NIAC), we evaluated the feasibility of the SGL for direct multipixel imaging of an exoplanet (Turyshev et al., 2018). We identified several practical challenges and determined that there are no fundamental limitations either with the concept or the required technologies. We analyzed the requirements with respect to operating a spacecraft at such enormous distances with the needed precision, studying i) how a space mission to the focal region of the SGL may conduct high-resolution direct imaging 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. Importantly, we determined that the foundational technologies already exist, and their development is already underway.

2 Technical Overview

Theoretical foundation: A wave-theoretical description of the SGL (Turyshev & Toth, 2017) demonstrated its remarkable optical properties. The SGL amplifies the brightness of faint sources by many orders of magnitude (i.e., ~10^{11} for $\lambda = 1$ μm), not achievable with conventional astronomical instruments. Its angular resolution is ~0.1 nas, making it well-suited for imaging distant objects.

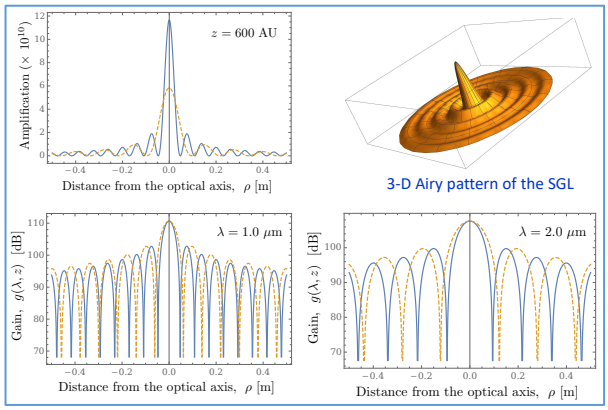

Figure 2. Optical properties of the SGL (Turyshev & Toth, 2017). Up-Left: Amplification of the SGL. Up-Right: Point spread function. Bottom: SGL's gain as seen in the image plane as a function of possible observational wavelength.

Consider an Earth-like exoplanet at 30 pc. Its angular diameter is 1.4×10^{-11} rad. To resolve the disk of this planet as a single pixel, a telescope array with a baseline of ~89.6 km is needed. Resolving the planet with 1,000 linear pixels would require a baseline of ~10,000 km (~$12R_\oplus$), which is not feasible.

In contrast, a modest 1 m telescope, at the focal line of the SGL at 750 AU from the Sun, can sample the light field of the SGL with a collecting area equivalent to that of a diffraction-limited telescope with an aperture of ~90 km and the angular resolution of an optical interferometer with a baseline of $12R_\oplus$. But even with such a baseline, this instrument will take millions of years to collect enough light to overcome the noise from zodialc light, needed to reach SNR of 7.

Our understanding of the optical properties of the SGL improved with our recent efforts. Figure 2

shows the SGL's point spread function (PSF), resolution and light amplification, all of which are essential parameters to the design of an SGL mission.

Imaging concept: The image of an exoplanet, for instance at 30 pc, is projected 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 focal half-line. Imaging an exoplanet at 1,000 × 1,000 pixels requires using the spacecraft as a single-pixel detector measuring the overall brightness of the Einstein ring, and moving it 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 PSF of the SGL is quite broad (see Figure 2), falling off much more slowly than the PSF of a thin 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.

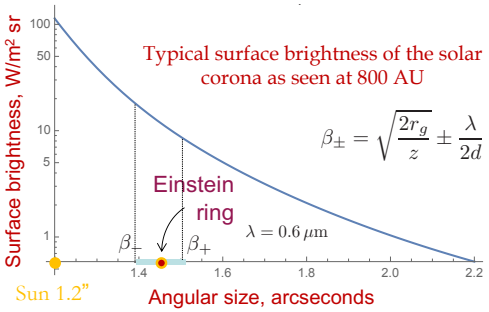

Figure 3. Solar corona brightness, as seen by the telescope at the focal area of the SGL.

Knowledge of the PSF's properties makes it possible to apply deconvolution algorithms to reconstruct the original image. These algorithms require a significant signal to noise ratio (SNR). Fortunately, the light amplification of the SGL makes a SNR of over 10^3 achievable over just 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 field of view, 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, see Figure 5), a small diffraction-limited high-resolution spectrograph is sufficient for the unambiguous detection of life (Turyshev et al., 2018).

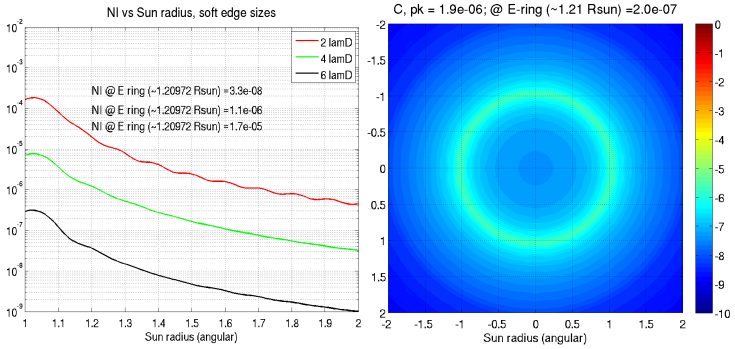

Figure 4. Left: Gaussian soft-edge has a great impact on light suppression ability of the coronagraph. Right: Simulated coronagraph performance showing the solar light suppression by 2×10^{-7}, sufficient for SGL imaging.

As the instrument ultimately determines the size of the spacecraft, 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 (Figure 3).

At 1 μm, the light amplification of the SGL is equivalent to −28.2 mag, so an exoplanet, initially seen as a 32.4 mag object, now becomes a ~4.2 mag object. Averaged over a 1 m telescope, light amplification is reduced to −23.25 mag. The exoplanet becomes a 9.2 mag object, still quite bright. However, the image will include noise in the form of light from the solar corona, the residual solar light, and the zodiacal light. Assumptions were validated by a 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 exoplanet at least as a single pixel.

We evaluated the performance of the coronagraph with a Fourier-based diffraction model. The Sun is modeled as a dense collection of incoherent point sources. The corona is represented by a power law profile of $\sim r^{-3}$ at the relevant heliocentric ranges. Design parameters include the telescope size, distance from the Sun, 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 4).

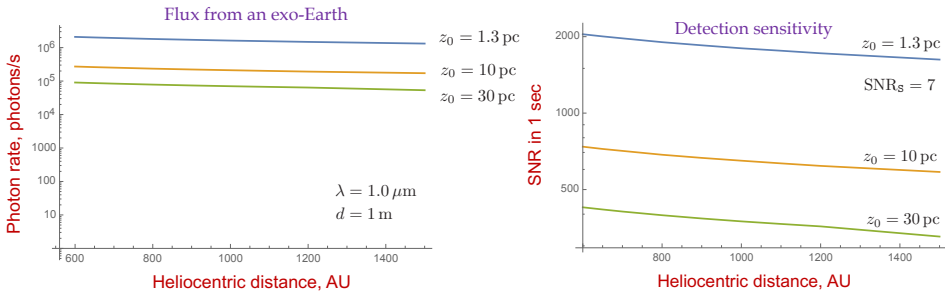

Figure 5. Left: Photon flux received from an exo-Earth at different heliocentric distances. Right: Detection sensitivity (i.e., the SNR in 1 sec) for exo-Earth at different distances.

Defining contrast as brightness normalized to peak brightness without coronagraph, we achieved a total planet throughput of ~10%. Figure 4 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).

Sensitivity estimates: A telescope operating at the focal region of the SGL at various heliocentric distances would see a strong signal. Assuming that we observe a system like the Sun-Earth system at various distances, namely 1.3 pc, 10 pc and 30 pc, we estimated the corresponding photon fluxes. Figure 5 shows that depending from the distance to the exoplanet, the flux will be at the level of 10^5-10^6 photons/s. Ignoring contributions from the solar corona, this translates into a significant SNR in 1 s, shown in Figure 5. Such a healthy, amplified signal may be used for imaging. Next, we include the noise contribution from the solar corona and estimated the realistic resolution that may be achieved. Figure 6 shows that over one year of integration time, it is possible to achieve an impressive pixel resolution of a distant target. As heliocentric distances increase and the Einstein ring further separates from the Sun, the contribution from the solar corona gets ever smaller, yielding higher SNR and thus, higher resolution.

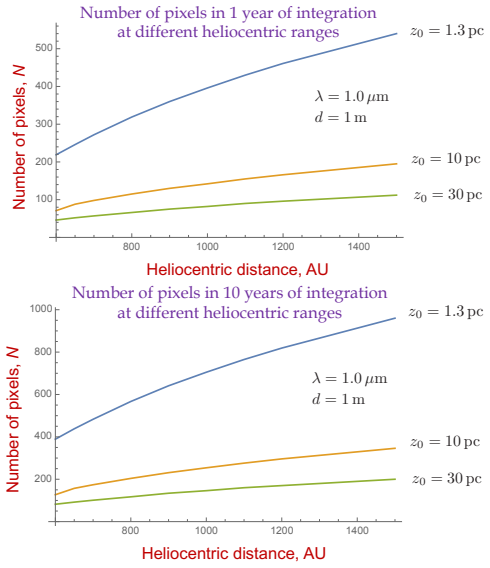

Figure 6. Image resolution with SGL and the solar corona: Top: 1 year. Bottom: in 10 years.

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. Rotational

deconvolution yields super-resolution that allows us to see a major part of the surface of the exoplanet in a few months of integration time; it would also allow us to peak under the cloud cover.

Using direct deconvolution and a 1 m telescope, it would take ~1.2 years to build a 500 × 500 pixel image of the entire planet (Figure 7). 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 $T \propto N$. 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 $T \propto d^{-3}$. Thus, a larger image of 1,000 × 1,000 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 include i) the rotational motion of a crescent exoplanet, and ii) the increase in heliocentric distance and the resulting improvements in coronagraphic performance.

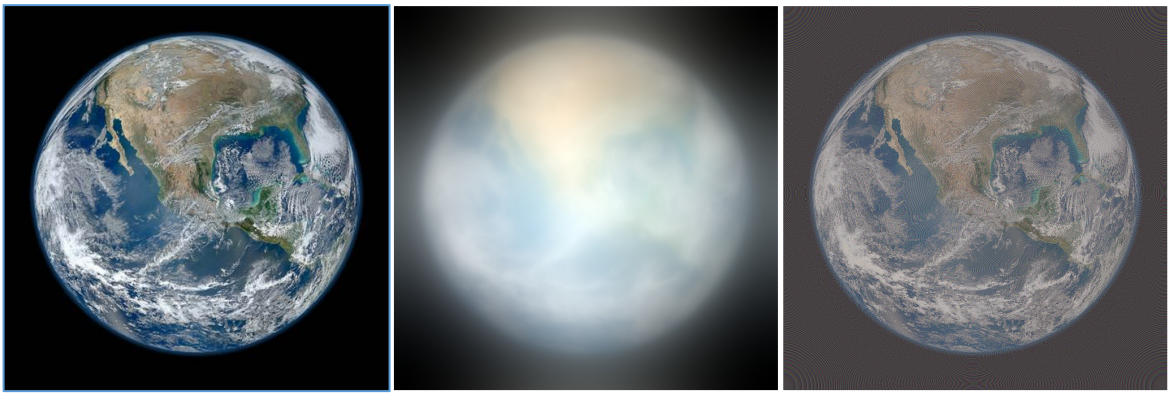

Figure 7. Deconvolving broadband images. Left: Original image. Center: convolution with the SGL. Right: Deconvolved image. Major features are clearly visible. Spatially resolved spectroscopy is possible. As the telescope aperture is much larger than the first minimum of the PSF, the actual SGL's amplification is wavelength independent.

Turyshev et al. (2018) have shown that although imaging with the SGL is complex, no fundamental "showstoppers" exist. Given the enormous light amplification provided by the SGL, spectroscopic investigations, even spectro-polarimetry could be viable. Ultimately, we 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 exoplanet.

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 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 collect light for millions of years. An SGL-aided instrument could do this job in a few years.

3 An approach for science implementation: reaching and operating at the SGL focal region

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 less than 30

years requires traveling ~8 times faster than Voyager 1. In addition, to assemble an image from brightness measurements of 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 ~10^3 (if not 10^6) times easier than competing approaches to observe an exoplanet, which would involve the huge (and enormously expensive) task of building kilometer-scale instrumentation in space. Furthermore, all the technologies required for a mission to the SGL are already either in development or operational.

Propulsion options: To get to heliocentric distances beyond 600 AU in 30 years or less, a heliocentric velocity of over 30 AU/yr is required. To achieve this speed, we considered several propulsion options that and may be broadly presented as follows:

1. Perihelion Propulsion (via Oberth maneuver) that includes two options: a) solid rocket motor that possesses a very high propellant-to-inert-mass ratio, and b) solar thermal propulsion with a specific impulse of I_s ~800-1000 seconds.
2. Outbound Propulsion (electric), which includes four options: a) Solar Electric Propulsion (SEP), which can be used to initially accelerate the probe in the inner solar system then coast, b) Radioisotope Electric Propulsion (REP) that is scalable to a ~100-500 kg spacecraft, c) Nuclear Electric Propulsion (NEP) with somewhat higher thrust-to-mass ratio, but with an overall mass being >2,000 kg, and d) Laser Electric Propulsion, that is based on beamed energy that allows for a very high thrust-to-mass ratio, but eventually the laser is too far away.
3. Outbound Propulsion (sails), that includes three options: a) Solar Sail, which offers a propellantless acceleration in the inner solar system, b) Electric Sail, that is pushed by the solar wind to allow to achieve thrust further out, and c) Laser Sail, offering an option that could allow for a very high initial thrust, but requiring a very high power laser.

Although, some exotic options exist, including fusion and thermonuclear pulsed propulsion, we opted not to consider them. Also, laser electric, nuclear electric, and nuclear thermal systems require major policy and funding changes in the space program; thus, they were also not considered at this time.

Perihelion propulsion requires carrying and firing a large motor with propellant very close to the Sun (<3R_S). How close is shown in Figure 8: to reach the required velocity out of the solar system would require a solar flyby of a 2-3R_S. The spacecraft must carry a large (heavy) thermal shield to enable a very close solar flyby. It would clearly mean a very expensive spacecraft and development of an elaborate heat shield. NASA is studying this approach now.

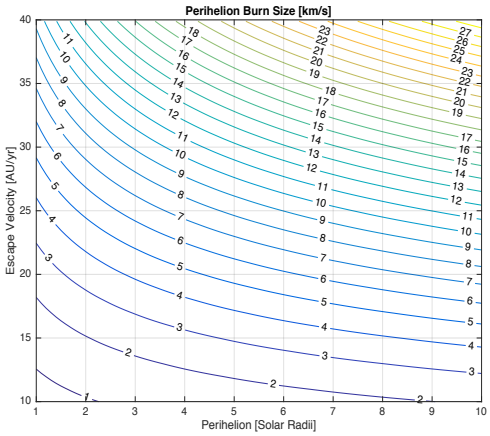

Figure 8. Perihelion propulsion trade space.

The two other options—solar and electric sails—have the advantage of carrying no propellant and not having to go so close to the Sun, perhaps "only" to 0.1 AU (20 R_S). They also use no propellant or large propulsion motors as they are propelled by the Sun. They are therefore compatible with a small spacecraft design, taking advantage of the rapidly advancing technology of smallsats. These will be lower cost and can incorporate multiple spacecraft or swarm architectures. Solar sails in particular have now flown on several missions, one in fact traveling interplanetary distances to Venus (the Japanese IKAROS mission). This is compelling, as it can lead to affordable spacecraft development that can be replicated for multiple targets and multiple

objectives. However, the advantage of no required propellant comes with the disadvantages of no maneuvering capability far from the Sun and no natural source of power. A small RTG or other nuclear battery system and electric propulsion micro-thrusters will be required for the relatively small amount of maneuvering Δv that will be required.

The electric sail is a new concept, which was only theoretically studied thus far. Solar sail spacecraft are flying, and the technology is developing with advanced materials and lightweight deployable structures. Our current SGL mission study is thus focused on the smallsat solar sail, but we recommend that a more comprehensive tradeoff study be conducted for cost and mission implications of the different propulsion options.

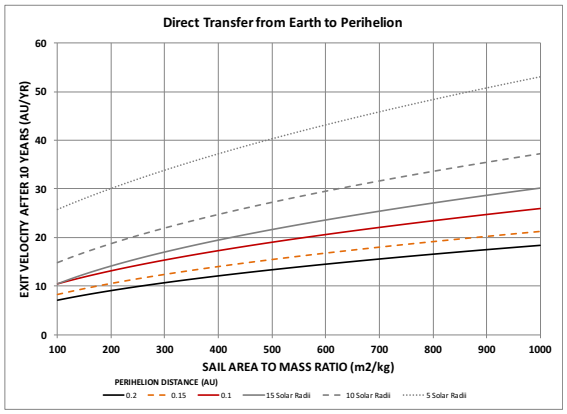

Figure 9. Design trade space for a direct transfer from the Earth to the perihelion using sail propulsion.

The speed of the solar sail spacecraft is dependent on area, mass and the thermodynamic properties of the sail material. This is illustrated in Figure 9, which shows heliocentric velocity as a function of spacecraft area-to-mass (A/m) ratio for different values of solar perihelion. To reach a velocity of > 20 AU/yr, we seek an A/m of over 200 m^2/kg and perihelion at <0.15 AU (30 R_S). A 200 × 200 m sail propelling a 50 kg spacecraft and flying at ~0.1 AU will exit the solar system at a speed of ~25 AU/year, which is higher than the velocity achievable with the other practically possible means of propulsion discussed earlier. This is a feasible design goal.

Sailcraft: The solar sail spacecraft can be launched at very low energy with a small launch vehicle or even as a secondary payload. It will then spiral in toward the Sun, offering the opportunity for solar corona observations, and then, after its closest solar flyby be oriented for the maximum sunlight pressure to exit the solar system at high velocity. The trajectory is shown in Figure 10.

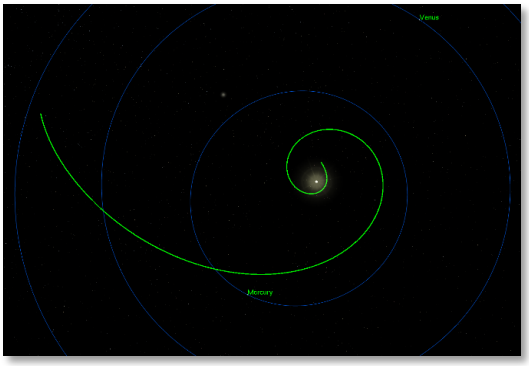

Figure 10. A sailcraft solar system exit trajectory.

Current solar sail materials are made of aluminized polymers or polyimides, e.g. Mylar™, Kapton™. These may be produced as ultrathin (1-2 μm thick) large films. While current solar sail technology has been successfully tested in a number of near-Earth and inner solar system missions, an interstellar flight with a close perihelion slingshot is beyond the reach of current sail technology. Indeed, sail materials will need to withstand an expected solar radiation flux >400 times then what reaches Earth, extreme solar plasma and encounter with high energy particles without degradation of performance. Aluminized polyamides absorbing over 10% of solar radiation will simply heat well above the melting point of both aluminum and polyamide. Novel materials with very low solar absorptivity (desirably <1%) and very high thermal emissivity (>0.8) that can withstand extreme temperatures and solar environment over the propulsion phase would be needed. In our study we have analyzed a wide range of high temperature materials. While refractory metals, such as tungsten and molybdenum, possessing very high melting points may seem promising, they absorb over 30% of sunlight and serve as very poor thermal emitters causing them to heat to extreme temperatures.

Refractory ceramics with high electronic band gap, such as alumina, silica, magnesium difluoride and boron nitride, in contrast, are nearly transparent, implying that a small fraction of sunlight is absorbed (~1%). We further showed that by structuring (e.g., with nanoscale lithography), thin sub-micron thick films of these ceramic materials may be made high reflective ensuring efficient solar radiation pressure harnessing. Large area fabrication of such nanopatterned ultrathin films will be informed by standard scalable processes, such as solution processing techniques and roll-to-roll CVD materials growth. In addition, recent deployment of roll-to-roll high resolution nanolithography would enable fabrication of desired patterns.

Our studies indicate that with the use of such high temperature nanostructured ceramics ultralight weight solar sail materials (<1 g/m^2) permitting 10 R_S flyby are possible. These sails would permit exit velocities in excess of 25 AU/year. The lighter the spacecraft, the greater the exit velocity and shorter the flight time. The size of the spacecraft will be principally determined by the telescope size and the spacecraft power needed. Electric power will drive the micro-thrusters used to maneuver the spacecraft in the focal region. Anticipated maneuver distances of 1 km are not large. Even to go from one exoplanet's focal line to another in the same star system is feasible. Surveys of an entire exoplanetary system can be done.

On-board propulsion: A preliminary design suggests that small micro-electric thrusters powered by ~5 watt of power will be sufficient. The largest maneuver required is that due to solar wobble, the motion of the sun around the barycenter of the solar system. Navigation will be done using first the host star's focal line for guidance and then maneuvering to the exoplanet's focal line. Figure 11 shows that the small amount of Δv and fuel required for maneuvers. A system like the TRAPPIST system with multiple potentially habitable planets can have its exoplanets' focal lines traversed, permitting imagining of several exoplanets on a single mission.

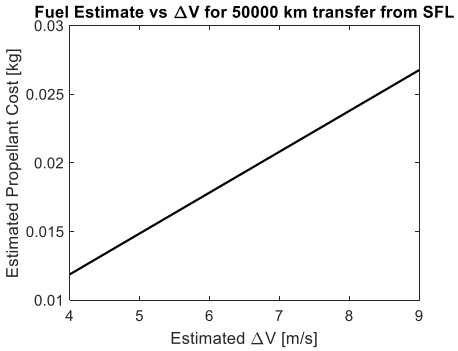

Figure 11. Δv, fuel needed for maneuvering.

In fact, 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.

Power & Communication: Power and communications are two of the technological challenges for a spacecraft operating beyond 650 AU. Fortunately, technology programs in NASA already are dealing with both. A laser communications system with today's technology operating at 1.35 μm with a 40 cm transmitting telescope to a 2.5-m receiver can provide a data 80 bits/second data rate over 200 AU and even 12.5 bits/second over 500 AU. These data rates yield 48 and 15.6 Mbits/week respectively – sufficient for download images continuously.

Small RTG power is a special need, but even with old technology, a single NASA MMRTG provides 27 watts electric with a mass ~10 kg. RTG usage on smallsats is the subject of current research but even adapting old technology suggest that a total spacecraft mass < 50 kg is possible.

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 and communicate with the Earth. A multiple spacecraft architecture may enable a robust communication architecture.

Multiple Spacecraft Architecture: The resulting smallsat can be a conceptually simple design, one

whose cost might be moderate enough to permit multiple spacecraft to be deployed. The multiple spacecraft approach may permit a communications relay system over the large interplanetary distances involved. Different spacecraft might also have different instrumentation. Some can be devoted to fields and particles measurements in the interstellar medium. As the mission trajectory goes in toward the Sun, it may be used to establish a corona-net in a near circular orbit of several satellites continuously monitoring the Sun from many vantage points. An Artificial Intelligence (AI) algorithm design is being investigated to manage a constellation of spacecraft in the focal region of the SGL. A multi-spacecraft architecture permits dividing and specializing mission functions between different spacecraft. One concept under study is to fly the coronagraph and imager on different spacecraft and using measurements from the former to delete the coronal effect on the latter. Another concept is to instrument some of the spacecraft specifically with interstellar medium fields and particles instruments. Others may have instruments to be used only during the close Sun flyby for studying its corona or be targeted for close Kuiper Belt object flybys. These ideas are conceptually possible but need to be considered in a mission design tradeoff study.

Organization, Partnerships, and Current Status: Currently, a number of organizations involved in the study of the SGLs science applications as well as in the relevant architecture and mission design studies. The collaboration includes NASA Jet Propulsion Laboratory, Caltech, The Planetary Society, The Aerospace Corporation, UCLA, NASA Marshall SFC, University of Arizona, Tucson, Texas A&M University, NXTRAC Inc., individual collaborators in Canada and Europe. We are engaged with Breakthrough Initiatives via their StarShot Project. There are several synergistic NIAC efforts, including Princeton Satellite Systems, UCSB, Wichita State University. In addition, there is a great pubic interest and engagement in the mission objectives.

Schedule: The challenges of getting to and operating from the focal region of the SGL are significant and require us to be able to (i) deconvolve the image collected pixel-by-pixel by measuring the exoplanet's Einstein ring; (ii) reach the solar gravity lens focal line for the exoplanet beyond 650 AU from the Sun in a reasonable mission time (e.g., less than 30 years), requiring a heliocentric velocity over 20 AU per year; and (iii) carry out this deep space mission with smallsats to permit an affordable and robust mission design. However, these challenges are not showstoppers; they may be addressed if a focused effort is initiated in the coming decade.

Much remains to be done. Technology programs, including the flight demonstration of the sail to low perihelion and high solar system exit velocity, the laser communications system and the long-life development of electric micro-thrusters should be accomplished in 5-7 years. The mission to the focus of the SGL will then be ready for flight development beyond the conceptual phase. The immediate need is to place this mission into the 2020s decadal planning so that a broad technology and system study can be conducted with specification of mission and technology requirements.

Cost: We cannot yet provide a serious cost estimate – a mission study to this end is the principal recommendation of this white paper. The conventional propulsion (chemical or solar thermal close to the Sun or nuclear thermal or nuclear electric) will likely be of Flagship class. The smaller spacecraft approach with solar sail will more likely be no larger than New Frontiers, similar to the New Horizon spacecraft now travelling in the Kuiper Belt. Incorporating new technology will be largely funded by space technology programs which, in our current study recommendation, includes a technology test flight inward to the Sun to test all the solar sail and smallsat design. The recommended mission study should develop the multiple mission concept with a total cost of about one billion dollars. A mission to observe extraterrestrial habitability and life for one billion dollars will be the greatest bargain in the history of space exploration.

4 Tear Down the Stovepipes – Perform a Mission Design Study

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 multipixel imaging of an exoplanet. All the exoplanet imaging concepts currently considered 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, the 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.

Discovery and identification of extraterrestrial life is surely the most significant and important goal of space exploration. And, its most elusive one. No matter how strong the hints, e.g.: atmospheric discoveries of water, methane, oxygen or surface feature and color changes; anything short of a close-up observation of an unmistakable life process will be debated. On an exoplanet, there is only one practical way to get such close observations: using the 100 billion times magnification power of the SGL to observe the planet over months and years. Is this possible? This question is the subject of our 3-year NIAC study (Turyshev et al, 2018).

Concluding, we would like to confront what is perhaps an even bigger challenge: breaking down the stovepipes within the Science Mission Directorate. The mission's science goals are within the scope of astrophysics, but the focus in astrophysics is on large telescopes trying to make one-pixel *indirect* images of exoplanets. The mission trajectory through the deep interstellar medium is of interest to heliophysics, but the focus there is reaching only a bit further than has Voyager with faster spacecraft for fields/particles measurements. Mission operation, the detailed and continuous observation of a planetary surface, is planetary science, but the current focus there is on planets in our solar system. The proposed concept employs a multi-spacecraft architecture and mission design, which will enable carrying out secondary science objectives in heliophysics and planetary science, while focusing on the principal goal of sending back high-resolution images of a likely habitable, possibly inhabited exoplanet. To consider any of this, however, first the stovepipes must be broken down, so that a serious mission study with this new architecture can be considered.

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). 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 and 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 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.

This work is partially supported by NASA Advanced Innovative Concepts (NIAC) and is performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Contributions from the Keck Institute for Space Science (KISS) and the Aerospace Corporation are also acknowledged.

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