DRAFT 16 May 2017

First Stop on the Interstellar Journey:
The Solar Gravity Lens Focus

Louis Friedman *[1], Slava G. Turyshev[2]
[1] Executive Director Emeritus, The Planetary Society
[2] Jet Propulsion Laboratory, California Institute of Technology

Abstract

Whether or not *Starshot*[i] proves practical, it has focused attention on the technologies required for practical interstellar flight. They are: external energy (not in-space propulsion), sails (to be propelled by the external energy) and ultra-light spacecraft (so that the propulsion energy provides the largest possible increase in velocity). Much development is required in all three of these areas. The spacecraft technologies, nano-spacecraft and sails, can be developed through increasingly capable spacecraft that will be able of going further and faster through the interstellar medium. The external energy source (laser power in the *Starshot* concept) necessary for any flight beyond the solar system (>~100,000 AU) will be developed independently of the spacecraft.

The solar gravity lens focus is a line beginning at approximately 547 AU from the Sun along the line defined by the identified exo-planet and the Sun[ii]. An image of the exo-planet requires a coronagraph and telescope on the spacecraft, and an ability for the spacecraft to move around the focal line as it flies along it. The image is created in the "Einstein Ring" and extends several kilometers around the focal line – the spacecraft will have to collect pixels by maneuvering in the image[iii]. This can be done over many years as the spacecraft flies along the focal line. The magnification by the solar gravity lens is a factor of 100 billion, permitting kilometer scale resolution of an exo-planet that might be even tens of light-years distant. The value of such an image would be enormous.

A mission to 500-1000 AU is a small fraction of interstellar flight, approximately 0.3%. Yet, its requirements are beyond current spacecraft state-of-the-art. A 50-kg spacecraft with a solar sail of 300x300 meters, capable of flying to 0.1 AU perihelion distance can reach 600 AU in 20 years and 1000 AU in about 33 years. Achieving this is a tall order: we do not have sails of this size, we do not have materials for this close a flyby of the Sun, and we do not have working smallsat (<100 kg) spacecraft for a 20-40 year journey. But meeting these requirements are necessary soon, if we are going to create even lighter spacecraft to capture the external energy which can enable interstellar flight. Other types of sails besides solar sails may also be considered – for example, e-sails, drawing power from the interaction of the solar and interstellar wind with charged wires on the spacecraft. Hybrid propulsion with sails and nuclear electric propulsion are also to be considered as is a new idea for laser electric propulsion since the spacecraft will likely require a small nuclear power source for operating hundreds of AU from the Sun. Studies are needed both for their cost-effective application to a solar gravity lens focus mission and their technology applicability as an interstellar precursor.

The solar gravity lens focus is the only destination in the interstellar medium (except for possible unknown rogue planets) that can serve as a milestone for interstellar flight. Beyond the heliopause (~120 AU) there are no natural objects which have compelling science and mission goals. If we can operate a spacecraft on the focal line created by the solar gravity lens we can in principle provide high resolution images of an identified interesting exo-planet, one that might itself be itself a fundamental interstellar goal. Because the spacecraft technologies necessary to operate such a mission are those which must be developed for interstellar flight it also serves as a technology driver. These include laser communications, deep-space/long-lived power, autonomy and reliability over long flight times, precise attitude control and stability and the materials and thermal technologies for very close flyby of the Sun. Thus, a putative solar gravity lens focus mission is both a scientific interstellar

precursor (imaging the identified potentially habitable exo-planet) and a technology precursor for interstellar flight. No other such precursor has been identified.

Rationale

The question of life on other worlds is perhaps the key question of space exploration. The discovery of a huge number with huge diversity of planets around other stars strongly suggests that putatively habitable planets will be discovered soon, perhaps even with bits of data suggesting that there is extraterrestrial life. But even if there is such discoveries no telescope we can imagine construction on Earth or in the accessible solar system will be powerful enough to resolve or characterize life. For example the angular size of an Earth-sized planet at 4.5 light-years (the closest star) is of the order of one milli-arcsecond, which would require a telescope on Earth (or anywhere in the inner solar system) with diameter of tens of kilometers. And that would provide only a one pixel resolution!

Fortunately, nature provides an alternative – a natural lens with a magnification power at 1 micron wavelength of 100 billion and extreme angular resolution of one billionths of an arcsecond! It is the solar gravity lens (SGL) which focuses light from a distant planet or star at along a semi-infinite line emanating away from the Sun beyond 547 AU (fig. 1).

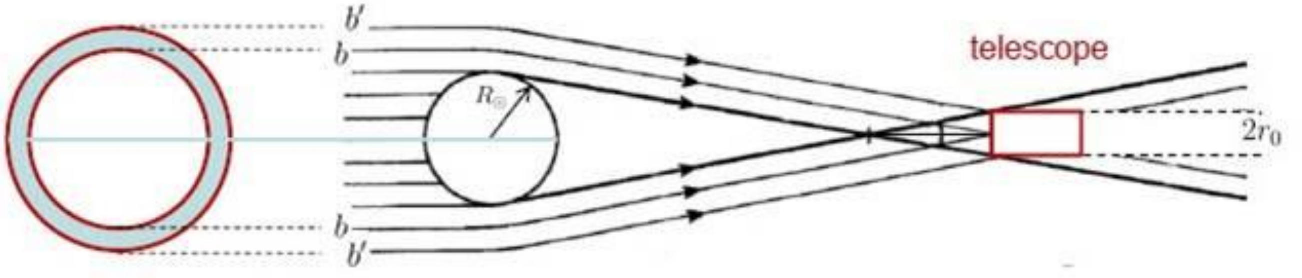

Figure 1

A modest telescope equipped with a coronagraph could operate at the SGL's focus to provide a direct high-resolution image and spectroscopy of an exoplanet. Because of the high magnification and tremendous resolving power of the SGL, the entire image of an exo-Earth is compressed by the SGL into a small region with diameter of 2 km in the immediate vicinity of the focal line [3]. While all currently envisioned NASA exoplanetary concepts (see https://exoplanets.nasa.gov/) aim at getting just a single pixel to study an exoplanet, a mission to the SGL focus opens the breathtaking possibility of direct imaging (at $10^3 \times 10^3$ linear pixels, or ~10 km in resolution) and spectroscopy of an Earth-like planet up to 30 pc away, enough to see its surface features and signs of habitability. Such a possibility is truly unique and should be studied in the context of a realistic deep space mission.

To derive an image with the SGLF, including contributions from the Sun (the parent star will be resolved at the anticipated resolution), and zodiacal light. A conventional coronagraph would block just the light from the Sun, but here we want the coronagraph to transmit light only at the Einstein ring where the planet light would be. Imaging with SGLF will be done on a pixel-by-pixel basis. It is likely that we would have to conduct a raster scan moving the spacecraft in the image plane. For the light received from an exoplanet, each pointing corresponds to a different impact parameter with respect to the Sun, thus, one image pixel. Between the adjacent pointings (i.e., pixels) the impact parameter changes, bringing in the light from the adjacent surface areas on the planet. To build a ($10^3 \times 10^3$) pixels image, we would need to sample the image pixel-by-pixel, while moving in the image plane with steps of $2\text{km}/10^3 = 2\text{m}$. This can be achieved, for instance, by relying on a combination of inertial navigation and 3 laser beacon spacecraft placed in 1 AU solar orbit whose orbital plane is co-planar to the image plane.

Considering the plate scale: with SGL, the image at the exo-Earth is reduced by a factor of $\sim 6\times10^3$, meaning the orbit of 1 AU becomes $\sim 2.25\times10^4$ km and orbital velocity of 30 km/s becomes 5 m/s. For comparison, the solar gravity accelerates the Earth at 6 mm/s^2. Similarly, the imager spacecraft needs to accelerate at ~6 μm/s^2 to move in a curved line mimicking the motion of the exoplanet. If the telescope is ~10^3 kg, the force is 6 mN, which may be achieved with electric propulsion. Whether it is feasible for interplanetary propulsion, electric propulsion may be sufficient for maneuvering to sample the pixels in the Einstein ring needed for imaging.

The instrument 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). In fact, relying on the enormous amplification and angular resolution of the SGL, a mission to the SGLF should also do spectroscopic research of the exoplanet, even spectro-polarimetry. Ultimately, it will not just be an image of the alien world, but potentially a spectrally resolved image over a broad range of wavelengths, providing a powerful diagnostic for the atmosphere, surface material characterization, and biological processes on an exo-Earth.

Given that interstellar flight to an exoplanet is beyond any known capability in any reasonable time frame this may allow us to unambiguously determine and characterize life on a planet around anther star. Even if interstellar flight is proved feasible it is almost certain that its imaging and data return properties will be very limited, insufficient for life determination on a target exo-planet. In short: imaging a putative habitable exo-planet at the solar gravity lens focus is likely the most practical way we will ever be able to accurately see such another world. A mission to the SGL will enable a breakthrough in exploration of habitable or better yet inhabited planets – decades, if not centuries, before being able to visit them.

How Can We Reach the Focus - >547 AU

The Voyager spacecraft has gone the furthest and fastest exiting the solar system at a speed slightly more than 3 AU/year. It will not reach 547 AU until after the year 2400 – long past its operating lifetime. A study at the Keck Institute for Space Studies (KISS) in 2014-15 considered the question of faster missions to go deeper into the interstellar medium to explore it, Kuiper Belt Objects and perhaps reach the solar gravity lens focus (SGLF).[iv] A mission design using an Oberth maneuver (applying a Δv at perihelion) with a large solid rocket motor can provide a much larger exit velocity.   Figure 2 (from the KISS Study) shows the exit velocity in AU/year as a function of the amount of Δv applied at perihelion (an Oberth maneuver) and the perihelion distance (from N. Arora in [5]). Applying this maneuver at low perihelion requires a significant heat shield. The system design sized for a SLS launch described in [5] provided a Δv=5.5 km/s at a perihelion of 3 solar radii (requiring heat shields totaling nearly 300 kg). The resulting exit velocity is ~13 AU/year.

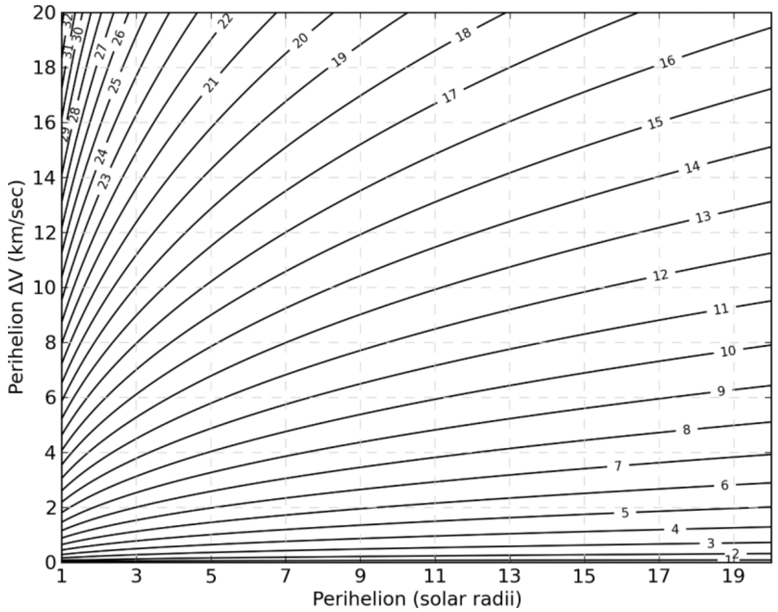

Figure 2

Arora, Strange, Alkalai[v] expanded the consideration of ballistic trajectories to include multiple gravity-assists for missions encountering Kuiper Belt Objects on the way into the Interstellar Medium literally examining thousands of trajectories. The result was a highest exit velocity of about 14 AU/year – insufficient for a practical mission to the SGLF. They also considered hybrid designs with a solar sail deployed on the trajectory after the close solar flyby while still in the inner solar system, after jettisoning the solid rocket motor and heat shields. For the designs, they considered they found that that exit velocities near 18 AU/year might be possible.

John Brophy at JPL has studied electric propulsion to reach that distance and found that a two-stage SEP/NEP system, with 30 kW SEP and 20 kW NEP can achieve 20 AU/year in about 20 years flight time[vi]]. It requires a small nuclear reactor for the NEP and would take at least 40 years to reach 547 AU. Brophy is now studying a new concept, powering an electric propulsion spacecraft with a 100-megawatt laser (space based) to reach an exit velocity of 40 AU/year, enabling a flight time of about 14 years to 547 AU.[vii] The use of a space-based 100 MW laser is a big assumption, but pales compared to the suggestion of the 500 GW laser in *Starshot.*

Friedman and Garber[viii]] first considered the SGLF as an interstellar precursor. They studied solar sail requirements to reach exit velocity speeds > 20 AU /year. The results are summarized in figure 3. Garber has extended this analysis to consider the area/mass requirements to reach an exit velocity of up to 40 AU/year. His result (private communication) is given in Figure 4:

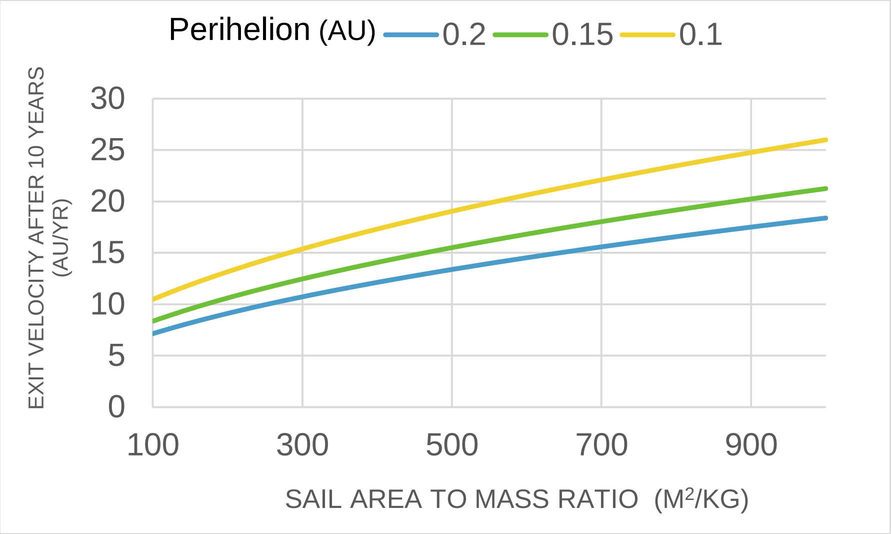

Figure 3

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. 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 15 years ago[ix] cited an Advanced Radioisotope Power System delivering 106 watts weighing 8.5 kg (~12.5 watts/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. N. Arora (private communication during the KISS study op. cit. estimated the REP boost might be as much as 20%, e.g. 5 AU/year. Albeit, likely with a heavier system.

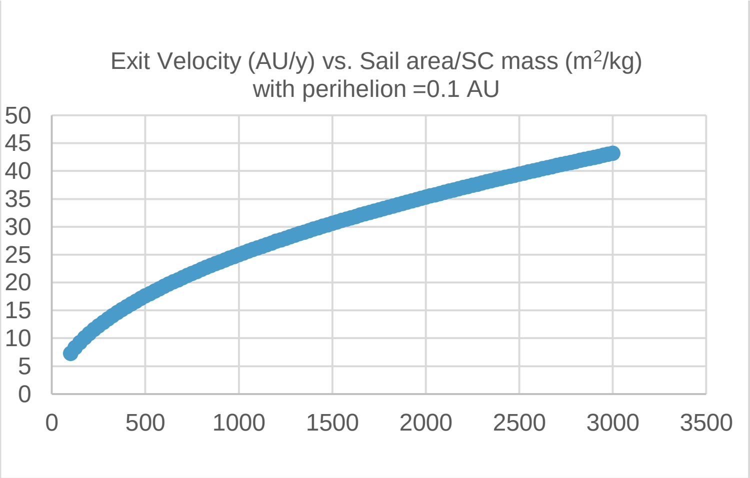

Figure 4

Thus, a 200 x 200 meter sail might achieve a solar system exit velocity of 25 AU/year with a notional mass statement for this example of

- 30 kg spacecraft bus;

- 13 kg for REP system providing 100 watts of electric power and possibly a small maneuver capability. It remains to be determined if the REP system can be smaller, or can add to exit velocity with a propulsive boost
- 1.6 kg sail whose density is on the order 0.04 g/m^2 (equivalent to 0.25-micron polyimide or a possible sail on carbon nanotubes). Of note is an interesting analysis of possible carbon nanotubes sails for extremely fast space flight, possibly as high as 0.001c (63 AU/year).[x]

The solar sail numbers are promising, although it must be emphasized that the largest area to mass designs that ever been built is ~ 8 m^2/kg; a long way below 900 or 1170 m^2/kg. (For comparison purposes we note that JPL mid-1970s proposal for a Halley Comet Rendezvous Mission used a solar sail spacecraft with an area to ass ratio of 711 m^2/kg,) Neither have any large sail areas been made with thickness <2.5 microns (one order of magnitude than that assumed above). Further study of practical solar sail sizes for a 20-30-year deep space flight, and of the minimal mass for long-lived interplanetary spacecraft remains to be done. If the spacecraft mass can be smaller, the sail area will correspondingly decrease (the sail linear dimension proportional to the square root of the mass).

A new consideration for space-sailing is the electric sail (or E-sail)[xi]]. This uses the solar wind instead of solar pressure and long charged tethers to propel the spacecraft by the created electrodynamics force resulting from the electric tethers flying through the charged particles of the solar wind. The advantage of e-sailing is that the force drops off much more slowly than the r^{-2} law of solar photons energy, due to a current sheath enlargement partially compensating for the decrease in solar wind energy. Pekka Januhen, the originator of the concept, made a preliminary estimate of the size required to reach 550 AU in 25 years with a 50 kg spacecraft: 20 tethers, 10 km each (200 km of total tether length). But E-sails are entirely theoretical at this point and many details about materials and spacecraft dynamics need to be considered. It would also of course require a radioisotope electric power source.

One might ask about laser sailing – it is, after all, a necessary technology for interstellar flight. It would be desirable to have the interstellar precursor be a laser sail. Phil Lubin is comprehensively studying (and experimenting with) laser sailing, with the goal of producing an interstellar roadmap.[xii] Figure 5 (presented by Lubin in the KISS study, op. cit.) shows that to achieve even 20 AU/year (~10^5 m/s) that the laser would require more than 100 GW with a telescope of 1km in order to propel a 10 kg spacecraft. This would be an interstellar precursor, but we do not want to wait for the long-desired (by some) but very problematical huge laser array. That same objection applies to the laser electric propulsion being studied by Brophy (op.cit.).

We conclude that solar sails are the only technology ready now to be considered for an interstellar precursor mission to the SGLF. Studies of E-Sail, and considerations of electric propulsion should continue, but no designs are practical now.

What Do We Have to Do There

When we reach the SGLF 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 focal line (cf. fig.1). That is the spacecraft will have to sample in a moving annulus some tens of kilometers in width 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 30 pc away, the planet's image moves in a 45,000-km diameter 1-year orbit. Its image at the SGLF is 2 km in diameter. One way to scan the image of an exo-Earth is a spiral scan to follow the planetary motion using a 2-km tether and the RTG on the other end of it. This reduces the fuel requirement for raster scanning the image.

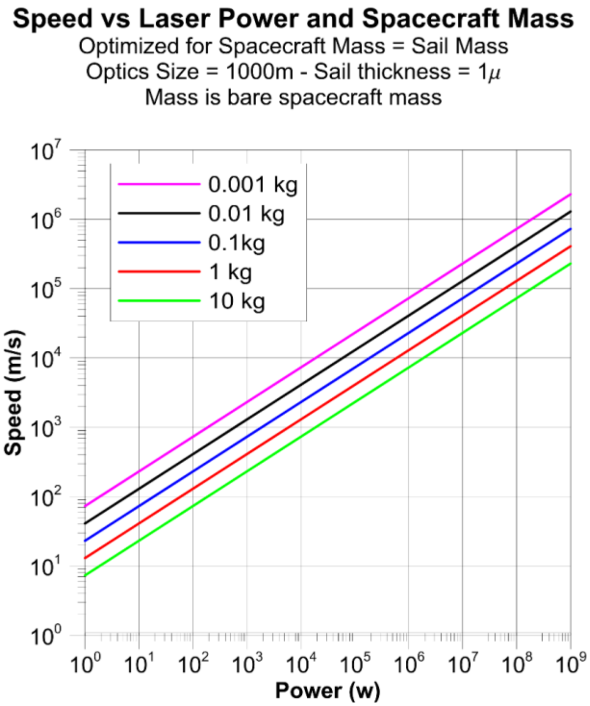

Figure 5 - Speed in m/s from Lubin (op.cit); 10^5 m/s= approx.. 20 AU/year

The relatively small amount of propulsion for such maneuvers cannot come from the sail (indeed, it may be jettisoned by then), but will have to come from the radioisotope power source being carried on-board. In addition the data will have to be communicated continuously back to Earth – likely with an optical system, although consideration of radio communication using the sail as an antenna remains to be done. A very high degree of stability and control will also be required.

Another approach for maneuvering in the Einstein Ring would be to have a subsatellite to the main satellite to carry the camera and collect the pixels. The sub-satellite could be tethered to the main spacecraft or perhaps, as suggested by Darren Garber (private communication) electrostatic forces between the main spacecraft and the sub-satellite could be used with very modest power in this plasma-free area of the interstellar medium. This novel means of propulsion control (for the sub-satellite) should be studied.

Implicit in the mission design is the a priori identification of the exo-planet which is our imaging target. The spacecraft can only go to one solar gravity lens focus. Thus, from the outset, the building of multiple small spacecraft should be planned both for reliability and to enable missions to image different exo-planets.

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 with aperture of 39.3 m that is currently under construction in Chile. A telescope with diameter of tens of kilometers in space is beyond our technological reach. Although very exciting, the SGL still needs a structure to support its use.

It remains to be determined just how complex will be the capturing and creation of exo-planet images using the solar gravity lens. It also remains to be determined what would be the cost of a mission to its focus. But 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 an exo-planet in another star system. This is especially true if the most interesting exo-planet to explore happens not to be at the nearest star but perhaps somewhere further away. In any case, the first job is to simulate creating the image in the SGLF. This is being done by Turyshev in his current NIAC study. We plan to investigate spacecraft design questions of how to reach the extremely large regions outside the solar system, but the primary emphasis will be placed on the feasibility of mission operations in support of the primary science objectives – the high-resolution imaging and spectroscopy.

The solar gravity lens may offer a unique means for imaging exo-planets and determining their habitability. The 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 would be an interstellar precursor advancing technologies ultimately necessary for interstellar flight and investigating the chief objective of an interstellar mission: the questions of life on other worlds.

This work, in part, was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

---

[i] A. Finkbeiner, Near Light-Speed Mission to Alpha Centauri, Sci Am, March 2017

[ii] S.G. Turyshev, B-G. Anderson, The 550 AU Mission: A Critical Discussion, Mon.Not.Roy.Astron.Soc. 341 (2003) 577-582, gr-qc/0205126

[iii] S.G. Turyshev, Wave-Theoretical Description of the Solar Gravity Lens Focus, Phys. Rev. D 95, 084041 (2017); arXiv:1703.05783 [gr-qc]; Slava G. Turyshev, Viktor T. Toth, Diffraction of electromagnetic waves in the gravitational field of the Sun, arXiv:1704.06824 [gr-qc]

[iv] E. Stone, L. Alkalai, L. Friedman, Science and Technology for Exploring the Interstellar Medium, Keck Institute for Space Studies Report, 2015.

[v] N. Arora, N. Strange, L. Alkalai, Trajectories for a Near-Term Mission to the Interstellar Medium, AAS 758, 2017

[vi] J. Brophy, private communication

[vii] J. Brophy, NASA Innovative Advanced Concepts Study, in progress, 2017

[viii] L. Friedman, D. Garber, Science and Technology Steps into the Interstellar Medium, IAC-14,D4,4,3,x22407 , International Astroanutical Congress 2014

[ix] R. Medwaldt, P. Liever, An Interstellar Probe Mission to the Boundaries of the Helisosphere and Interplanetary Space, AIAA Space Forum, 2000

[x] S. Santoli, Carbon Nanotube Membrane Solar Sails, in Marulanda, Carbon Nanotubes, 2012

[xi] P. Janhunen et. al., Overview of Electric Solar Wind Sail Applications, Proceedings of the Estonian Academy of Sciences, 2014, 63, 2S, 267–278

[xii] P. Lubin, A Roadmap to Interstellar Flight, JBIS, 2016.