MISSION TO THE SOLAR GRAVITY LENS FOCUS: NATURAL HIGHGROUND FOR IMAGING EARTH-LIKE EXOPLANETS L. Alkalai[1], N. Arora[1], M. Shao[1], S. Turyshev[1], L. Friedman[8] ,P. C. Brandt[3], R. McNutt[3], G. Hallinan[2], R. Mewaldt[2], J. Bock[2], M. Brown[2], J. McGuire[1], A. Biswas[1], P. Liewer[1], N. Murphy[1], M. Desai[4], D. McComas[5], M. Opher[6], E. Stone[2], G. Zank[7], [1]Jet Propulsion Laboratory, Pasadena, CA 91109, USA, [2]California Institute of Technology, Pasadena, CA 91125, USA, [3]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA,[4]Southwest Research Institute, San Antonio, TX 78238, USA, [5]Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA, [6]Boston University, Boston, MA 02215, USA, [7]University of Alabama in Huntsville, Huntsville, AL 35899, USA, [8]Emritus, The Planetary Society.

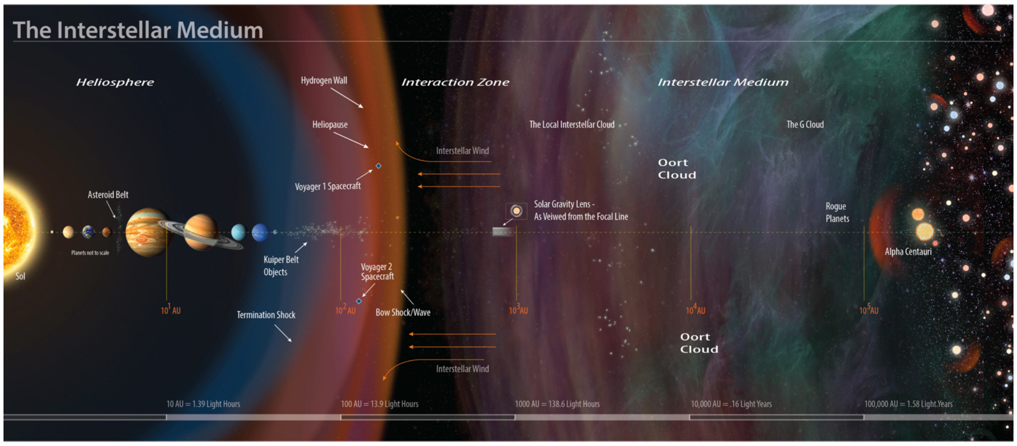

Figure 1: A SGL Probe Mission is a first step in the goal to search and study potential habitable exoplanets. This figure was developed as a product of two Keck Institute for Space Studies (KISS) workshops on the topic of the "*Science and Enabling Technologies for the Exploration of the Interstellar Medium*" led by E. Stone, L. Alkalai and L. Friedman.

Introduction: Recent data from Voyager 1, Kepler and New Horizons spacecraft have resulted in breath-taking discoveries that have excited the public and invigorated the space science community. Voyager 1, the first spacecraft to arrive at the Heliopause, discovered that the interstellar medium is far more complicated and turbulent than expected; the Kepler telescope discovered that exoplanets are not only ubiquitous but also diverse in our galaxy and that Earth-like exoplanets are not unusual; and New Horizons has revealed an unexpected Pluto with remarkable features suggesting a varied range of Kuiper Belt Objects (KBO). These results inspire intellectual curiosity, new scientific questions, and bold mission concepts reaching far into the deep interstellar medium and one day to exoplanets.

Science Rationale: Recent reports from the Kepler telescope provide a wealth of targets of opportunity for additional remote sensing using ground-based telescopes and current and future space-borne assets. However, all of these assets currently in existence or under consideration for deployment in the near future, are limited by the telescope aperture size or the interferometric baseline distance. The natural high-ground for multi-pixel imaging of exoplanets resides along the line (region) called the Solar Gravitational Lens (SGL) Focus (or foci) that takes advantage of the fact that the Sun's large gravitational field focuses light from faint, distant sources into the SGL region.

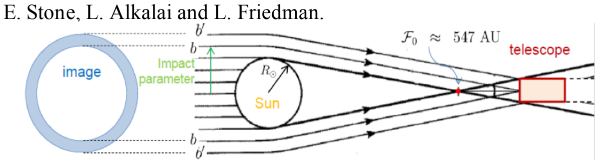

Fig. 2. Imaging of an exo-Earth with solar gravitational Lens. The exo-Earth occupies (1km×1km) area at the image plane. Using a 1m telescope as a 1 pixel detector provides a (1000×1000) pixel image!

According to Einstein's general relativity, gravity induces refractive properties of space-time causing a massive object to act as a lens by bending light. As a result, the gravitationally deflected rays of light passing from around of the lensing mass converge at a set of focal points, as shown in Fig. 2, where the focal length is defined by the mass of the Sun. Of all the solar system bodies, only the Sun is massive enough that the focal length resides within range of a realistic mission from Earth. The focus of the SGL is a semi-infinite line that begins at ~550AU from Earth (Figure 2).

While all currently envisioned NASA exoplanetary imaging concepts aim at getting just a small number of pixels (in most cases just one) to study an exoplanet, a mission to deploy a small telescope at the SGL opens up a revolutionary possibility for direct (1000×1000) pixel imaging and spectroscopy of an Earth-like planet up to 30 parsecs (pc) away, 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 merits a detailed study in the context of a realistic mission.

We present a daring and breakthrough mission concept to the SGL Focus (SGLF, ~550 AU) to deploy an optical telescope capable of direct imaging of an Earth-like exoplanet at unprecedented resolution.

Possible Mission Instrumentation: The SLGF mission instrument would be a ~1m telescope with a large focal plane, 0.4° field of view (FOV) with point-spread function (PSF) Nyquist-sampled and metrology systems that would calibrate instrumental errors in the focal plane and optics at the µas level. The instrument will require a miniature diffraction-limited high-resolution spectrograph, taking full advantage of the SGL amplification and differential motions (exo-Earth rotation).

The telescope will use a coronagraph to block the light from our Sun. At 1 µm, the gain of the SGL is ~110dB (27.5 mag), so an exoplanet, which is 32.4 mag object, will become a ~4.9 mag object. When averaged over a 1m telescope (the gain is $\sim 2\times 10^9$), it would be 9.2 mag, which is sufficiently bright (even on the solar background). 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. Instrument design should be matured in a detailed study. Trades between a single big telescope versus multiple smaller telescopes should also be evaluated.

Mission Concept Design: As of 2016, Voyager 1 has traveled a distance of ~137 AU from the Sun in 39 years since its launch, and is travelling at ~17.26 km/s relative to the Sun. It recently entered the Interstellar Medium (ISM) and is humanity's first (functioning) interstellar spacecraft. To reach the SGL the spacecraft needs to travel a distance of ~550 AU. A spacecraft travelling at the speed of Voyager 1 will take >150 years to reach the SGLF. To make the SGLF mission viable, an order of magnitude reduction in trip time is needed.

We have set the following mission goals, to be achieved using near-term technology coupled with innovative mission design concepts:

1. Reach the local ISM (100-120 AU) in < 8-10 years, compared to Voyager's 120 AU in 40 years.
2. Reach the SGLF in <50 yrs. from launch for exoplanet imaging using an optical telescope.
3. Perform Heliophysics, Astrophysics, ISM, KBO fly-by investigations on the way to SGLF.

As pointed out in the KISS ref. design study, multiple mission design options exist to realize such a mission and can be broadly classified into two types: 1) mission requiring a powered Jupiter flyby, 2) mission requiring a perihelion maneuver deep in Sun's gravity well (3-4 solar radii). Recent work has shown that it is possible to achieve solar-system exit speeds in excess of 15 AU/Yr. More optimized mission concepts may result in even higher escape speeds. Given the high launch energies, the SGLF mission is uniquely enabled by using the NASA's upcoming heavy lift launch vehicle, SLS.

The KISS design reference mission (DRM 1.0) along with recent papers on this topic has shown that a pathfinder precursor mission can be deployed as early as 2025 that would demonstrate all the basic elements of the mission architecture including a perihelion (Oberth) maneuver using advanced thermal protection system, and other relevant capabilities. A subsequent mission with scaled capabilities can then achieve the goal of placing an optical observatory to the SGLF for the detailed imaging of Earth-like exoplanets.

Spacecraft Technologies: The spacecraft for this mission would benefit from the ongoing small-spacecraft (CubeSat) revolution and will require a highly integrated, fault tolerant flight system design capable of lasting in excess of 50 years from launch. Given, the high launch energy and large mission ΔV requirements, emphasis has to be placed on reducing mass and power on the spacecraft. Spacecraft power would rely and benefit from latest advancements in radioisotope power system (RPS) technology. There are already efforts at JPL to advance the lifetime of existing RPS technology. The challenge of communication from SGL with reasonable data rates and power requirements can be addressed by using a hybrid radio and Deep Space Optical Commutations system.

The proposed mission concept builds upon the technology under development for the Solar Probe Plus (SPP) mission that will launch in 2018, to survive the thermal environment at perihelion. A more detailed look at optimizing the heatshield design and spacecraft thermal protection system is required. Finally, the spacecraft should have sufficient autonomy/re-configurability so that it detects, reacts and recovers from a multitude of off-nominal conditions with advanced autonomous capabilities.

Programmatic Considerations: Given the multidisciplinary nature of a mission deep into the ISM and the SGL, programmatic creativity is essential for mission success. Stakeholders for the SGLF mission include: ExoPlanets, Astrophysics, and Planetary Science. Heliophysics will also be interested to add small instrument package on the mission.

SGLF Probe Notional Timeline	
<2020	Solidify Baseline mission, technical feasibility and instrument prototype
Early 2020s	Acquisition of SLS launch slot.
2020s	Launch
2030s	Enter local ISM, do ISM and KBO science
>2060s	Reach the SGL, start exoplanet imaging
>2080s	Go beyond into the unknown