FOCAL: Deep Space Science and Telecommunications Using the Sun's Gravitational Lens

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Co-Investigators: Dr. Claudio Maccone,[ii] Dr. Eric Davis,[iii] and Dr. Michael LaPointe[iv]

Abstract: Predicted by the General Theory of Relativity and confirmed by experimental observations, incident electromagnetic radiation can be focused by gravitational lenses created by the mass of astrophysical objects such as galaxies, stars, and even planets. In the case of our Sun's gravitational lens, incident electromagnetic waves are focused along a line beginning 550 AU from the Sun; a probe traveling away from the Sun at or beyond a distance of 550 AU can use the Sun's mass as a huge magnifying lens to obtain detailed radio, optical, or higher frequency observations of distant astrophysical sources located behind the Sun such as the recently discovered planet orbiting Alpha Centauri B or one of the myriad extrasolar planets discovered by the Kepler Mission. Gravitational lensing has also recently been investigated as a method to enable robust telecommunications with future interstellar probes (potentially allowing 2-way communication using as few as 100W) and, as a communication bridge between stellar systems as we expand into interstellar space. Although the potential applications of gravitational lensing have been previously studied and published (for example, Maccone's FOCAL mission), no significant work has yet been performed to evaluate the actual mission requirements for sending an instrumented spacecraft to the minimum 550 AU focal point of the Sun and out along the focal line. We propose to perform this analysis assuming well defined targets of scientific interest, and to identify the requirements for performing a FOCAL observing mission for the first time.

Background: Gravitational Lens of the Sun

Briefly, the geometry of the Sun's gravitational lens may be described as follows. Incoming electromagnetic waves from a distant source pass outside the Sun, within a certain distance, *r*, of its center (Figure 1). From General Relativity, the Schwarzschild solution[1] provides the corresponding deflection angle $\alpha(r)$ at a distance r from the Sun's center:

$$\alpha(r) = \frac{4GM_{Sun}}{c^2 r}$$

Electromagnetic waves cannot pass through the Sun's interior, so the largest deflection angle occurs for rays just grazing the Sun surface ($r = r_{Sun}$). This yields the inequality $\alpha(r_{Sun}) > \alpha(r)$, where:

$$\alpha(r_{Sun}) = \frac{4GM_{Sun}}{c^2 r_{Sun}}$$

From Fig. 1, the minimal focal distance, d_{focal}, is related to the tangent of the maximum deflection angle by the formula:

$$\tan(\alpha(r_{Sun})) = \frac{r_{Sun}}{d_{focal}} \approx \alpha(r_{Sun})$$

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The tangent is approximately equal to $\alpha(r_{Sun})$ due to the small angle size (≈ 1.75 arcsec). Equating the last two equations and solving for the minimal focal distance d_{focal} yields:

$$d_{focal} \approx \frac{r_{Sun}}{\alpha(r_{Sun})} = \frac{r_{Sun}}{(4GM_{Sun}/c^2 r_{Sun})} = \frac{c^2 r_{Sun}^2}{4GM_{Sun}}$$

Numerically, this yields:

$$d_{focal} \cong 8.27 \times 10^{13}\ \text{m} \approx 550\ \text{AU} \sim 3.17\ \text{light days} \sim 14\ \text{times the Sun-Pluto-distance.}$$

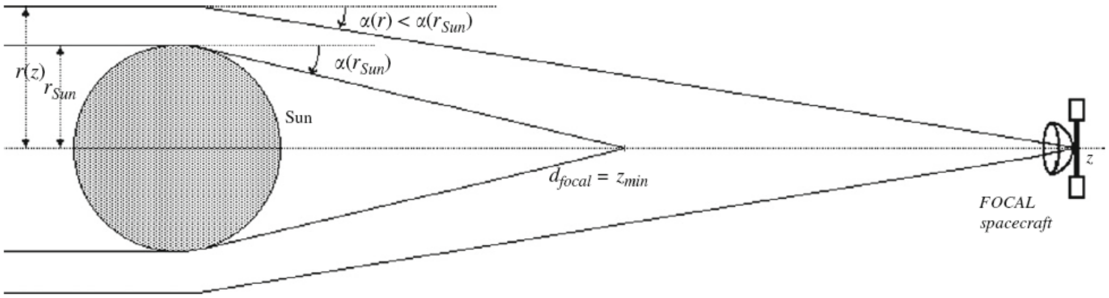

Figure 1 Basic geometry of the gravitational lens of the Sun (Maccone[2])

This minimum focal distance of the gravitational lens of the Sun, approximately 550 AU, corresponds to the minimum distance from the Sun's center a spacecraft must reach to obtain magnified images of sources on the other side of the Sun. In addition, as seen in Fig. 1, all points on the straight line beyond this minimum focal distance are foci as well, because rays passing the Sun at $r > r_{Sun}$ have smaller deflection angles and come to a focus farther from the Sun. As such, it is not necessary to stop the spacecraft at 550 AU; it can continue on its journey and focus distant sources just as well. Note that for radio astronomy applications, traveling beyond 550AU actually improves the imaging due to less distortion of the radio waves by the solar corona.

FOCAL Mission:[3] Study Approach

While the potential benefits of using the Sun's gravitational lens for astronomical imaging[4] and future deep space telecommunications[5] are well known, little prior work has been performed to define an actual mission architecture to enable such a bold and scientifically rich endeavor. Multiple questions remain regarding the feasibility of mounting such a mission, with several rudimentary details yet to be worked out. Defining the types of targets deemed to be of most scientific interest, we propose to develop the corresponding spacecraft and instrument architectures required to perform high priority FOCAL missions optimized for cost, schedule, and scientific return. Science missions could include mapping galactic and extragalactic sources in unprecedented detail at wavelengths ranging from radio waves to high energy x-ray and gamma-rays; high resolution imaging and spectroscopy of individual extrasolar planets such as α-Centauri Bb, Gliese 581c, or any of the growing number of potentially Earth-like planets recently discovered by the COROT and Kepler missions; it may even be possible to obtain panoramic vistas of distant solar systems such as Kepler-42, directly establishing planet size and distribution around a magnified host star. For telecommunication applications the Sun's gravitational lens can be used (and indeed may be required) to communicate with humanity's first truly interstellar probes, and as we eventually achieve future interstellar exploration capabilities, to establish robust, low power telecommunications between neighboring star systems using the gravitational lens of each stellar mass. As estimated by Maccone,[6] once set up such communications would require only a few hundred watts of power to maintain relatively error free communications at interstellar distances.

Sending spacecraft to 550 AU and beyond requires trades of power, mass, and mission time, all of which will be investigated during the NIAC concept study. Prior work related to potential TAU (Thousand Astronomical Unit) missions will be researched and leveraged, and optimized mission architectures for FOCAL spacecraft will be developed. Science investigations that can be performed along the route to 550 AU and beyond will be evaluated, leading to complete mission profiles with clearly identified scientific returns on investment. In Phase I, an architecture for one specific FOCAL mission will be selected and developed. OCT/NIAC representatives will be consulted to determine an initial target of interest for this investigation. In Phase II, the analysis will be extended to include detailed mission designs for additional scientific and deep space telecommunication applications, providing a representative taxonomy of FOCAL missions suitable to serve as a baseline for future mission planners.

Clearly, a mission to 550 AU and beyond will stretch the bounds of our current technologies; mission durations may last for decades, requiring robust spacecraft and instruments while simultaneously pushing the limits of our propulsion, power, and communication systems. But it is exactly these types of challenges that inspire innovation and ignite the imaginations of the next generation of scientists and engineers who would carry out such audacious missions. This proposal is a first step in laying out that path.

Team Members: Mr. Les Johnson will serve as the PI for this new NIAC mission concept study. Les is currently the Deputy Manager for the MSFC Advanced Concepts Office, where he performs and directs technical studies related to advanced space mission concepts. Co-Investigators include Eric Davis, a specialist in relativity theory and spacecraft engineering; Mike LaPointe, Deputy Manager for the MSFC Science Research Office, with additional expertise in deep space propulsion; and Claudio Maccone, Technical Director, International Academy of Astronautics, and a pioneer in the use of the Sun's gravitational lens for science, interstellar communication, and the search for life outside the solar system. Dr. Maccone is a permanent legal resident of the United States and is eligible for funded participation.

References:

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[1] Eshleman, V., "Gravitational lens of the Sun: its potential for observations and communications over interstellar distances," *Science* 205 (1979), 1133–1135.

[2] Maccone, C., The Sun as a Gravitational Lens: Proposed Space Missions, 3rd ed., IPI Press, Colorado Springs, CO, 2002 (ISBN 1-880930-13-7)

[3] The term FOCAL to describe missions to 550 AU and beyond was originally used by Maccone and is retained here to provide continuity with the prior studies.

[4] Maccone, C., "Realistic targets at 1000 AU for interstellar precursor missions," *Acta Astronautica* 67 (2010), 526–538

[5] Maccone, C., Deep Space Flight and Communications – Exploiting the Sun as a Gravitational Lens, Springer, Berlin/Heidelberg/New York, 2009 (ISBN978-3-540-72942-6)

[6] Maccone, C., "Interstellar radio links enhanced by exploiting the Sun as a Gravitational Lens," *Acta Astronautica* 68 (2011) 76–84

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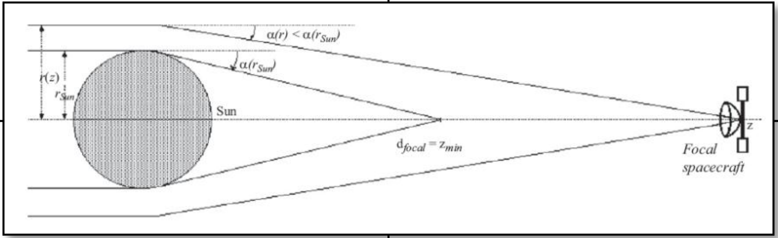
Concept

- Send instrumented probes to 550 AU and beyond, where the gravitational lens of the Sun can be used to obtain high resolution images of distant astrophysical objects (such as recently discovered extrasolar planets), and to provide telecommunication capabilities with future deep space probes.
- The large magnification provided by the solar gravitational lens at 550 AU and beyond will allow us to obtain unprecedented scientific results, such as the atmospheric spectra of remote Earth-like planets, detailed radio frequency maps of galactic and extragalactic sources, and high resolution images of energetic sources at x-ray frequencies and beyond.
- The lensing effect can be used (and may be required) to establish comm. links with interstellar spacecraft.



Benefits

- If successful, a FOCAL mission to 550 AU and beyond would enable:
  - Imaging and spectroscopy of extra-solar planets, including Earth-like planets recently discovered by COROT and Kepler
  - Detailed mapping of celestial radiofrequency sources, including regions near the currently obscure galactic center
  - High resolution x-ray imaging of energetic objects such as distant planetary nebula, black hole accretion disks, and other astrophysical objects of intense scientific interest
  - Robust, low power communications with deep space probes
  - *In situ* science measurements out to 550 AU and beyond
- The benefits of using the solar gravitational lens will be explored; the proposed study will provide a solid technical understanding of what it takes to mount such an audacious mission, and a better understanding of the science it enables.

Study Approach

- Develop mission architectures of sufficient fidelity to serve as representative baselines for future mission planners:
  - Identify a candidate set of missions, such as imaging and spectroscopy of an Earth-like planet in one of the recently discovered planetary systems, or high resolution imaging of a black hole accretion disk, to evaluate during this study.
  - Phase I: Evaluate spacecraft power, propulsion, mass, instrument payload, and trajectory requirements; top level costs; and expected duration for one such mission of interest.
  - Phase II: Extend the Phase I analysis to evaluate additional missions of interest, detailing FOCAL mission technical requirements and quantifying the benefits for deep space science and communications.

Evaluation Notes