Magnifying Light by 100 Billion Times
with the Solar Gravitational Lens for Direct Imaging of an Exoplanet

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... because we are all kids at heart...
A nice family portrait...

“The Earth is the cradle of humanity, but mankind cannot stay in the cradle forever.”
Konstantin Tsiolkovsky

But..., is there anybody out there?
Milky Way Galaxy

About 13.2 billion years old.
200–400 billion Stars, with at least 100 billion Planets, 500 million of which may support Life

125,000 Light Years in Diameter.

The Milky Way is moving at a rate of 552 to 630 km per second, being pushed away from the Local Void at 600,000 mph. Our Solar System travels at 447,000 MPH and takes 250 Million years to complete one Galactic Rotation.

You Are Here

26,000 light years away from the Black Hole at the center of the Milkyway
Current estimates:

- ~50% of stars have planets;
- ~100 billion stars in our Galaxy, and 1-10 planets per star;
- 50 billion to 5 trillion planets in our Galaxy (alone);
- There are ~10 new stars forming each year in our Galaxy…
- ~5 new planetary systems/year…
- ~5-50 new planets/year.

Exoplanet census (Aug 2018):

- 3,725 – confirmed;
- 4,496 – candidates;
- 2,778 – solar systems;
- 929 – terrestrial.

Finding Earth 2.0 is matter of time…
  – but what will we do once we find it?

https://exoplanets.nasa.gov/
Exoplanet astronomy is poised for a major growth with detection of millions of exo-planets expected.
The Kepler planets
European Extremely Large Telescope
39 meters, Chile (est. 2022)

The largest telescopes for the last 125 years to date, both on the ground and in space
The Solar Gravitational Lens

Largest telescopes in space

Telescope sizes compared

Webb will be the largest astronomical telescope ever put into space. Spitzer, the current infrared telescope, is tiny by comparison.

Mirror sizes

The size of the mirror makes the biggest difference in a telescope’s light-gathering capability.

- **Kepler**: 1.4 m
- **Hubble**: 94.5 inches (2.4 meters)
- **Human**: 255.6 inches (6.5 meters)
- **Webb**: 33.5 inches (0.85 meters)
- **Spitzer**: 33.5 inches (0.85 meters)
Exoplanet Missions

Habitable Exoplanet Imager
LUVOIR
AFTA-C
Exo-Coronagraph,
Exo-Starshade,
LUVOIR, AT-LAST,
HDST

Demographics
Characterization

Ground Telescopes with NASA participation

1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA
The size does matter...

...and so does the distance: *the tyranny of the diffraction limit...*
Our Challenge

A Pale Blue Dot
Our Stellar Neighborhood within 100 ly

Location of the Stars with Exoplanets within 100 light years

Credit: PHL @ UPR Arecibo, Jim Cornwell  phl.upr.edu, Jul 2013
The tyranny of the diffraction limit: To make a 1-pixel image of an exo-Earth at 100 light years, one needs a telescope with a diameter of ~90 km...
A (10k×10k)-pixels image of our Earth

This 2002 Blue Marble image features land surfaces, clouds, topography, and city lights at a maximal resolution of 1 km per pixel.

Composed from 4 months data from NASA's Terra satellite by R.Simmon, R.Stöckli.
The tyranny of the diffraction limit: To make a 1,000-pixel image of an exo-Earth at 100 light years, a telescope with a diameter of ~90,000 km is needed...

Diameter of 90,000 km is ~7 diameters of the Earth.
THE SOLAR GRAVITATIONAL LENS
Mission to the Gravity Lens of the Sun

Eshleman V.R., Science 205, 1133 (1979)

Gravitational Lens of the Sun: Its Potential for Observations and Communications over Interstellar Distances

Abstract. The gravitational field of the sun acts as a spherical lens to magnify the intensity of radiation from a distant source along a semi-infinite focal line. A spacecraft anywhere on that line in principle could observe, eavesdrop, and communicate over interstellar distances, using equipment comparable in size and power with what is now used for interplanetary distances. If one neglects coronal effects, the maximum magnification factor for coherent radiation is inversely proportional to the wavelength, being 100 million at 1 millimeter. The principal difficulties are that the nearest point on the focal half-line is about 550 times the sun-earth distance, separate spacecraft would be needed to work with each stellar system of interest, and the solar corona would severely limit the intensity of coherent radiation while also restricting operations to relatively short wavelengths.

About 40 years ago, Einstein (1) published a short note in Science on the focusing of starlight by the gravitational field of another star. He emphasized the improbability of observing this phenomenon by the chance alignment of two stars and the earth. From concepts based on current technology and trends, however, it appears that gravitational focusing of electromagnetic radiation might be employed, by design, for highly directional observations and communications over interstellar distances.

In such use, the gravitational field of the sun could play several roles. First, it might be used to reduce fuel and time required for interstellar travel. Second, a focusing mechanism to extract the primary light from a distant source could be realized. Third, a mass of enameled scales along the circumference of a circle at the ray-impact radius. Using also the wave number \( k = 2\pi/\lambda \), the maximum intensification of the coherent signal is simply

\[ I_{\text{max}} = 2\pi k^2 \]

As an approximation, let the focal “spot” radius \( x_0 \) be the value of \( x \) where \( I \) falls to \( I_{\text{max}}/4 \), so that \( x_0 = (2/\pi k)(x_0/2g)^{1/2} \). Thus the angular resolution for distinguishing two adjacent coherent sources by a corresponding change in intensity is \( x_0/\pi \) radians. (The first null off the center line is at \( x = \pi\sqrt{x_0/2} \), and the first sidelobe is twice this distance with intensity \( I_{\text{max}}/\pi^2 \).) The periastron or minimum radius of the ray relative to the center of mass is \( a - g \), or essentially \( a \), and this must be greater than \( r_0 \), the physical radius of the spherical mass. Thus \( a_{\text{max}} = 2g/r_0 \) and the focal line begins at \( z_{\text{min}} = r_0^2/2g \).

Now consider the focusing at \( z = z_{\text{min}} \) of incoherent radiation from a uniformly bright, circular, extended source of radius \( r_0 \) and distance \( z_0 \gg z \). This is the problem considered by Einstein (1) and more completely by others, notably Liebes (4). The gain factor \( A \) of the gravitational lens for the intensity observed from the two individual image components

Optical wavelengths magnification \( \sim 10^{11} \)

Kraus J.D., Radio Astronomy, Cygnus-Quasar Books, Powell, Ohio, 6-115 (1986)
Maccone C., many papers, 1999-present
Precision alignment between a Lens and the Earth is very unlikely…
In 1913 Einstein wrote to Hale:
  – “Is eclipse necessary to test this prediction?”
  – Hale replied: “Yes, an eclipse is necessary, as stars near the Sun would then be visible, and the bending of light from them would show up as an apparent displacement of the stars from their normal positions.”

In 1914, the first attempt - a German expedition
  – A German astronomer Finley-Freundlich led an expedition to test the Einstein's prediction during a total solar eclipse on Aug. 21, 1914 (in Russia);
  – However, the First World War (July 28, 1914) intervened, and no observations could be made.
The First Test of General Theory of Relativity

Gravitational Deflection of Light:

\[ \alpha_{GR}(b) = \frac{2(1 + \gamma)GM_\odot}{c^2b} \approx 1.75 \left( \frac{1 + \gamma}{2} \right) \left( \frac{R_\odot}{b} \right) \text{ arcsec} \]

Solar Eclipse 1919: possible outcomes

- Deflection = 0;
- Newton = 0.87 arcsec;
- Einstein = 2 x Newton = 1.75 arcsec

Campbell’s telegram to Einstein, 1923

Einstein and Eddington, Cambridge, 1930
Gravitational Deflection of Light is a Well-Known Effect Today

Galaxy Cluster Abell 2218

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08
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Our solar system and tests of gravity
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40+ Years of Solar System Gravity Tests

Techniques for Gravity Tests:

Radar Ranging:
- Planets: Mercury, Venus, Mars
- s/c: Mariners, Vikings, Pioneers, Cassini, Mars Global Surveyor, Mars Orbiter, etc.
- VLBI, GPS, etc.

Laser:
- SLR, LLR, interplanetary, etc.

Dedicated Gravity Missions:
- LLR (1969 - on-going!!)
- GP-A,’76; LAGEOS,’76,’92; GP-B,’04; LARES,’12; MicroSCOPE,’16, ACES,’18; LIGO,’16; eLISA, 2030+(?)

New Engineering Discipline – Applied General Relativity:
- Daily life: GPS, geodesy, time transfer;
- Precision measurements, deep-space navigation & μas-astrometry (Gaia)

"for decisive contributions to the LIGO detector and the observation of

General relativity is now well tested. Can we use it to build something?
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The Solar Gravitational Lens (KISS study, 2015)

The Interstellar Medium

Heliosphere

- Asteroid Belt
- Hydrogen Wall
- Voyager 1 Spacecraft
- Interstellar Wind
- Interstellar Medium

Interaction Zone

- Heliopause
- Voyager 2 Spacecraft
- Bow Shock/Wave
- Interstellar Wind
- The Local Interstellar Cloud
- The Oort Cloud
- 4 light days

- Interstellar Wind
- Solar Gravity Lens - As Viewed from the Focal Line

- Interstellar Medium
- The Oort Cloud
- Alpha Centauri
- Rogue Planets

- 10 AU = 1.39 Light Hours
- 100 AU = 13.9 Light Hours
- 1000 AU = 138.6 Light Hours
- 10,000 AU = 1.6 Light Years
- 100,000 AU = 1.58 Light Years

The Solar Gravitational Lens

- \( \alpha_0 = \frac{2r_g}{R_\odot} \approx 8.5 \mu\text{rad} \rightarrow \alpha(b) = \alpha_0 \frac{R_\odot}{b} \)

- \( \mathcal{F}_0 = \frac{R_\odot}{\alpha_0} = \frac{R_\odot^2}{2r_g} \approx 547 \text{ AU} \rightarrow \mathcal{F}(b) = \mathcal{F}_0 \frac{b^2}{R_\odot^2} \)
Optical properties of the SGL: caustic

Different regions of the SGL

Caustic formed behind the Sun
• Major brightness increase:
  - For small departures from the optical axis, \( \rho \), magnification of the SGL is:

\[
\mu_z(\rho, z, \lambda) \approx 4\pi^2 \frac{r_g}{\lambda} J_0^2 \left( 2\pi \frac{\rho}{\lambda} \sqrt{\frac{2r_g}{z}} \right)
\]

- Max value of \( G(\rho, \lambda) \) is on axis:

\[
\mu_z(0, z, \lambda) \approx 4\pi^2 \frac{r_g}{\lambda}
\]

Gain of the SGL as seen in the image plane as a function of possible observational wavelength

Herlt & Stephani, IJMP 15, 45 (1976)

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The image within the Einstein ring

Credit: ESA, Hubble & NASA Wikimedia
Important features of the SGL (for $\lambda = 1 \, \mu m$):

- Major brightness magnification: a factor of $10^{11}$ (on the optical axis);
- High angular resolution: $\sim 0.5$ nano-arcsec. A 1-m telescope at the SGL collects light from a $\sim (10\text{km} \times 10\text{km})$ spot on the surface of the planet, bringing this light to one 1-m size pixel in the image plane of the SGL;
- Extremely narrow “pencil” beam: entire image of an exo-Earth ($\sim 13,000 \text{ km}$) at 100 l.y. is included within a cylinder with a diameter of $\sim 1.3 \text{ km}$.

Collecting area of a 1-m telescope at the SGL’s focus:

- Telescope with diameter $d_0$ collects light with impact parameters $\delta b \approx d_0$;
- For a 1-m telescope at 750AU, the total collecting area is: $4.37 \times 10^9 \text{ m}^2$, which is equivalent to a telescope with a diameter of $\sim 80 \text{ km}$...
Imaging Exoplanets with the Solar Gravitational Lens

Video Not Embedded in the PDF

https://www.youtube.com/watch?v=Hjaj-lg9jBs

Or see HAL5 website (www.HAL5.org) look for August 14, 2018 program page for video

Credit: J. DeLuca
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Do not point at the Sun!!!!

Granulation of solar surface

A solar flare

Coronal mass ejection

Approx. size of Earth
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Effects of plasma on the Solar Lens

• Total deflection: gravity & plasma

\[ \alpha_{\text{tot}} = \alpha_{\text{GR}} - \alpha_{\text{pl}} = \frac{2r_g}{b} - \alpha_{\text{pl}} \]

- Note the opposite sign. For observer: gravity bends the ray outwards, plasma inwards, and the different dependence on \( b \), plasma being steeper.

• Moving the interference zone out:

\[ \frac{b}{F_{\text{gr+pl}}} = \alpha_{\text{tot}} = \frac{2r_g}{b} - \alpha_{\text{pl}} \]

- For impact parameters \( b/R_\odot \in [1.05, 1.35] \)

\[ F_{\text{gr+pl}}(b, \nu) = 546 \left( \frac{b}{R_\odot} \right)^2 \left[ 1 - \frac{\nu_{\text{crit}}^2}{\nu^2} \left( \frac{R_\odot}{b} \right)^{15} \right]^{-1} \text{AU} \]

Refraction of radio-waves in the solar atmosphere: the steady-state model, and X- and K-bands radio freqs. The absolute value for GR is also shown.

Effective optical distances for different freqs and impact parameters. From top to bottom: 170 GHz, 300 GHz, 500 GHz, and last 1 THz.

For 1 um refraction in the solar corona is not an issue, but brightness needs to be addressed.
Solar corona brightness

Graph showing surface brightness and electron density as functions of distance from the Sun's center and Earth's orbit.
Coronagraph study: sun disc & solar corona

- Contrast @ E-ring: 2e-7
  - w/o corona: 1.4e-7
- E-ring planet core PSF throughput: ~ 10%
  - Lyot + Occulter over +/- \( \lambda/D \)
Albedo model high resolution map

Deep Space Climate Observatory (NOAA, Feb. 11, 2015):
Earth Polychromatic Imaging Camera (EPIC)
High SNR allows for

- High-resolution spectroscopy
- Allows reconstruction of a 2-D albedo map from annual variation of the disk-integrated scattered light using technique of spin-orbit tomography (i.e., rotational deconvolution)
- Next step is a direct deconvolution
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Image formation by the SGL

\[ I(x_2, \lambda) = O(x, \lambda) \otimes PSF_{\text{diff}}(x_2, \lambda) \]

\[ PSF_{\text{diff}}(x_2, \lambda) \approx J_0 \left( \frac{\pi |x|r_0}{\lambda f} \right) \otimes \frac{r_0}{|x_2|} \]

- \( r_0 \) – impact parameter,
- \( |x_2| \) – distance in the image plane,
- \( \otimes \) – 2D convolution operator.

Accretion disk around a black hole as a test object for convolution by the PSF of the SGL.

Image obtained after convolution. Photon noise is added, corresponding to 100 ph/pixel.

De-convolved image using the SGL’ PSF. Low-pass filtering in spatial frequencies is applied.

The solar wobble

Center of the Sun shown as dots monthly from 1944 to 2020 with actual size of the Sun shown at its average position, during this time period.

Astrometric displacement of the Sun due to Jupiter as at it would be observed from 10 parsecs, or about 33 light-years.
**Direct Multipixel Imaging and Spectroscopy of an Exoplanet with a Solar Gravity Lens Focus (SGLF) Mission**

An imaging mission to SGLF appears to be feasible, but needs further study

### Concept
- SGLF provides a major gain (~$10^{11}$ at 1μm), resolution of $10^{-9}$ arcsec in a narrow FOV;
- A 1-m telescope at ~750AU has a collecting area equivalent ~80 km aperture in space;
- A mission to the SGLF could image Earth 2.0 up to 30pc away with resolution to ~10km to see surface features;
- A small s/c with electric propulsion (or solar sails) can reach the SGLF in <35-40 yrs.

### Proposed Study and Approach
- Define baseline design, sub-syst components;
- Define mission science goals & requirements;
- Develop system and subsystem requirements;
- Study mission architecture and con-ops;
- Assessment of feasibility (cluster) small-sats;
- Identify technology development needs;
- Study instruments & systems: power, comm, pointing, s/c, autonomy, coronagraph, nav, propulsion, raster scan in the image plane, etc.

### Benefits
- A breakthrough mission concept to resolve a habitable exoplanet at modest cost/time;
- Could find seasonal changes, oceans, continents, life signatures on an exo-Earth;
- Small-sat & fast exit from the solar system;
- Electric propulsion for raster-scanning the image using tethered s/c (or cluster);
- SLGF is valuable for other astrophysics and cosmology targets.

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Earth with resolution of (1000 × 1000) pixels.
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Image of Our Earth in Physical Colors