Finding Earth 2.0 from the Focus of the Solar Gravitational Lens

Time and space and gravitation have no separate existence from matter.
—Albert Einstein's one-sentence description of General Relativity

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Interstellar flight is to us as was human air flight to DaVinci: We can dream, speculate, calculate and even conceptually design – but we cannot achieve. For DaVinci his ideas took some 400 years to be realized -- whether it will take more or less for interstellar flight – we do not know. We do not yet know when, nor how.

Is interstellar flight then only a subject of fiction? It is if we think the old-fashioned way: heavy people in multi-generational space ships or cryogenically cooled in stasis flying at warp speeds or through wormholes on propulsion systems whose physics we almost understand but whose engineering eludes us. Modern thinking suggest a different paradigm: extend human presence to the stars remotely and virtually allowing us to discover and explore a potentially human world decades or centuries earlier than would otherwise be possible – perhaps even in our lifetime!

Earth 2.0 remains out of reach not just of our machines, but also even over our observing horizon. To see a candidate Earth-like planet and determine how human-like it might be, potentially habitable for humans or inhabited by other life, is not within our reach. We can calculate the size of telescopes and capabilities of instruments to make such measurements over interstellar distances (potentially hundreds of light-years) but building them is not very foreseeable.

Recent reports from the Voyager 1 and Kepler missions have brought our attention to two important facts: Voyager 1 is the first spacecraft to have reached the interstellar medium where it is able to gather and transmit data from heliocentric distances beyond 130 AU; the Kepler telescope found that planets are ubiquitous in the Universe with many Earth-like exoplanets. In the coming decade we expect to learn more about Earth-like exoplanets with atmospheres, free oxygen, water and other indicators of habitability.

We soon will have a lengthy list of exoplanets similar to Earth 1.0 and are rapidly approaching the day when a major newspaper will open with a headline: "First habitable Earth-like exoplanet discovered!" What do we do the next day? How are we going to explore this alien world, very far from our own? Whereas sending missions to explore exoplanets in-situ is technologically beyond the scope of the present-day (or even foreseeable) technology, it is timely to begin to think about the first steps in the long path forward.

Nature comes to our rescue – general relativity's bending of light by our Sun creates a gravity lens through which we can image an extra-solar planet at terrestrial planet resolution, sharp enough to distinguish the characteristics of habitability. For visible light, the magnification is enormous - more than hundred billion, which comes with extreme angular resolution of better than a billionth of a second of arc -- all within a very narrow field of view. A one-meter telescope on the focal line of the solar gravity lens (SGL) at 750 AU from the Sun yields a collecting area larger than five thousand square kilometers, i.e., equivalent to a telescope with a diameter of over 80 kilometers!

Given its unique properties, the SGL could provide us with first direct *multi-pixel* high-resolution images and spectroscopy of a potentially habitable Earth-like exoplanet over 30 parsec away with resolution of 3×3km (1000x1000 pixels) on its surface. We could resolve continents, clouds, and putative artifacts on an Earth-like planet even hundreds of light-years from Earth. The solar gravity lens is a very powerful "instrument" that we have yet to explore. This would not be easy – but like the magnification factor, the engineering is a billion times less daunting than is interstellar flight and, if achieved, it would provide an Earth 2.0 for us on Earth 1.0.

First, let's consider what and where the focus of the solar gravitational lens is. Gravity influences all matter—even matter that has no mass itself, such as pure light. In 1704 Isaac Newton suggested that a light ray could be deflected by gravity. But only Einstein's theory of general relativity published in 1915 was able to provide a consistent description. General relativity describes gravity as a curvature of space-time and predicts that when light passes by an object of large mass its path would bend in that object's gravitational field. It was the famous bending of light from a distant star by the Sun, observed in 1919 by the British astronomer Arthur Eddington that provided the first empirical proof of general relativity—and made Einstein a household name worldwide.

Since the original Einstein prediction, gravitational bending of light had been confirmed in various observations and now is well understood. Light, say from a distant star or galaxy, passing close to the Sun is bent—more when the light passes near the Sun and less when it passes farther away. Light rays passing on the opposite sides around the Sun converge at a focus, which, because of the differential bending of the light rays at different distances from the Sun, is a series of points forming a line coincident with the line from the star through the center of the Sun — a whole line of focal points. When you work out the math of the angle that the light is bent, you find that the first point (nearest to the Sun) is 547AU along that line.

In fact, if perfectly aligned, the solar gravity field forms a lens in the shape of a narrow annulus around the Sun (known as the Einstein ring), magnifying the intensity of light from a distant source along that semi-infinite focal line beginning at 547 AU. This light, while magnified greatly, is still dimer than the Sun. However, a modest coronagraph would be able to block the solar light, so that the exoplanet's light could be detected at the telescope placed on that focal line.

At 547 AU, the Sun subtends ~3.5 seconds of arc ("). At a wavelength of one micron, the diffraction-limited size of a telescope is comparable to the size of the solar disk: a 1 meter telescope has a beam size of about 0.1''. Light in this narrow annulus would come from a spot approximately 3x3km on the exoplanet's surface. However, light from outside the annulus would come from other parts of the exoplanet, corresponding to a different Einstein's ring. This light will also be blocked by the coronagraph. In fact, because of the very high resolution of the SGL, the image of the exo-Earth at 30 parsecs would extend ~1.1km around the focal line at the location of the spacecraft beyond 547AU from the Sun. The spacecraft would have to scan this 1.1×1.1km area one pixel at a time to develop multi-pixel image of an exo-Earth with resolution of 1000×1000 pixels. Information from each of these spots will be deposited in a single pixel of the Einstein ring. De-convoluting that image can be done on the ground, but collecting all the information in our instruments and then transmitting the data back to Earth over hundreds of AU is the high-tech challenge with the high-payoff: the detailed high-resolution map of Earth 2.0. This is certainly something we can do in 100 years – perhaps even in 50 and thus fulfill the audacious goal of 100 Year Starship even sooner than hoped.

547 AU would be our distance goal if the Sun were a perfect static solid ball—but it isn't. The Sun has an active and dynamic atmosphere, the solar corona, with many particles that affect the beam of light passing close to the Sun. The light is not bent smoothly, and the actual minimum solar gravity lens focal distance is more like 700 AU. We set this as our mission goal—and in fact define the focal line from 700 AU to 1,000 AU as the mission objective for a solar gravity lens focus mission (SGLFM). A solar system escape trajectory for the mission could be timed to fly up a focal line (away from the Sun) corresponding to a pre-selected star identified as a scientifically interesting extrasolar planetary target—for example, an identified habitable planet. It could be the selected target for the first interstellar mission.

Every exoplanet-imaging mission concept currently envisioned by NASA, detects the light of the planet as a single pixel. The major problem has been contamination from the parent star that is 0.1" from the planet. A 1-m telescope at the SGL would collect the light from the approximate 3 km spot on the surface of the planet, bringing this light to one 1-m size pixel in the image plane of the SGL. Because of the high angular resolution of the SGL, the parent star will be completely resolved from the planet with its light being amplified many AU away from the optical axis provided by the direction to the planet, thus, removing the contamination issue.

An Earth-like planet at a distance of 30 parsec has an angular diameter of 0.014 nano-radians. A diffraction-limited telescope comparable in magnifying power to a 1-m telescope placed at the SGL would have a diameter of ~80 km. However, even this telescope would barely resolve the disk of the planet. To resolve the planet with 1,000 pixels across the planet one would need a telescope (or interferometer) with a diameter of 40,000km (or ~3 times larger than the Earth.) Even with a one-micron mirror, it would weigh about one million tons. And even, if realized, the solar radiation pressure would remove it from the solar system beyond the orbit of Pluto in less than a year. The SGLFM represents a far more feasible alternative.

Mission design for SGLFM presents many interesting challenges. Just reaching the solar gravitational lens focus in a reasonable amount of time is challenging enough. Distances beyond 500 AU can be achieved in practical flight times with solar sails flying toward the Sun to a perihelion of 0.1-0.2 AU. Spacecraft area to mass ratios are required larger than the current state of the art, but the requirements are consistent with those studied and considered in prior NASA and ESA studies. A solar system escape speed of 15 AU/year would reach 700 AU in 50 years and 1,000 AU in 67 years. This would require a 50x50 meter solar sail carrying a 9 kg spacecraft or equivalently a 166x166 meter sail carrying a 100 kg spacecraft—beyond today's state-of-the-art, but actually not beyond our current engineering capabilities and within the reach of current smallsat designs. Other ways of getting there might prove feasible, but currently the solar sail offers the more practical possibility.

A number of technologies will be combined into conceptual mission architecture. These include: (i) Optical communications with low mass, volume, and power, operating at large distances. (ii) Small spacecraft with large solar sails, (iii) Use of small radioisotope power generators, and (iv) Use of advanced materials to enable closer flyby of the Sun with a solar sail and potentially of electric sails. (v) Advances in autonomy, control, and the design of adaptive systems and, perhaps most interesting, (vi) the creation of the image in aforementioned Einstein ring. All of these technologies are expected to mature in the next decade, so that they could provide us with the means to realize the mission to the SGLF.

Our mission would choose a promising Earth-like planet and then target the focal line beginning at 700 AU, from that planet through our Sun, with a trajectory following that line outward. This would be done only after an Earth-like planet was discovered and characterized. Smallsat technology with their associated lower costs might permit multiple spacecraft to be developed for simultaneous missions along the focal lines of several promising Earth-like planets. In this way we could survey our universe for the first human interstellar goal.

The interstellar goal is alluring. In recent years we have two conclusions that seem to oppose each other. The first is that we are finding thousands of new worlds with a huge range of conditions, some suggestive of habitability or life, some bizarre not even close to life as we know or imagine it. Even in our own solar system we find several worlds of astrobiological interest (e.g. Europa, Enceladus, Titan) – habitable maybe, but not human accessible – even they will have to be studied through robot eyes. A plethora of worlds, many having some Earth-like characteristics, suggests optimism about a universe with ubiquitous life. The opposing viewpoint might be pessimistic – with all this activity still no sign of life beyond Earth: not distant, not nearby. Human spaceflight remains maddeningly slow: 45 years after humans reached the Moon they still have gone no further (and in fact went less far). We might make it on Mars sometime this century, but to make it an Earth 2.0 will take many centuries of terraforming and engineering. Finding Earth 2.0 will require something more innovative than bigger propulsion or giant telescopes. The solar gravity lens focus may not just be our best chance, it may be our only chance for the foreseeable future. It is hard and complicated, but going there with a machine that is capable of being powered, controlled, communicating and holding itself stable while flying in an Einstein ring 90 billion km from Earth and capturing that view of Earth 2.0 will truly create the 100 year starship.