SunLensing the Cosmic Microwave Background from 763 AU

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NASA intends to launch its "InterStellar Probe" (ISP) around 2010 toward the direction of the incoming interstellar wind: –16° in declination and +16.6 hours in right ascension. This mission will be going as far as possible away from the Sun. A 400-meter solar sail will make ISP reach 250 AU from the Sun in just 15 years, i.e. around 2025. This is well beyond where the Heliosphere ends with the Heliopause, and the interstellar space begins. Though all payloads aboard ISP will be devoted to study the Heliosphere, the Heliopause and the (possible) Bow Shock, the author of this paper suggested the ISP Team to put aboard ISP one more (small) instrument to perform an experiment called the "CMB SunLensing". This instrument could be either a photometer or a bolometer and its task is to observe the Cosmic Microwave Background (CMB) enormously magnified by the gravitational lens of the Sun.

To the "gravitational lens of the Sun" or "Sun's gravity lens" the author devoted his book described at the site http://www.ijvr.com/ipipress/maccone2.htm#top and awarded the "1999 IAA Book Award" by the International Academy of Astronautics (IAA) on October 3, 1999. In this paper, we just confine ourselves to saying that "SunLensing" is the lensing effect caused by the Sun's bending of spacetime according to general relativity: all light rays passing close to the Sun's surface are a little deflected toward the straight line (axis) from the source to the Sun's center and made to focus at a point opposite to the source with respect to the Sun center and located *at least* 550 Astronomical Units (AU) away from the Sun (i.e. 3.17 light days, or 14 times the Sun-Pluto distance). The magnification (radio amplification) provided by the Sun's gravity lens is huge (for instance, it equals 100 dB for a 12 meter antenna placed at 550 AU and observing on the neutral hydrogen line at 1420 MHz).

NASA's ISP is expected to reach the distance of 550 AU from the Sun in 2042, and that will be the first opportunity ever to check physically the magnifying properties of the Sun's gravity lens. Unfortunately, there is "nothing" (i.e. no quasar, or AGN, or bright star) on the celestial sphere in the direction opposite to the incoming interstellar wind direction, along which ISP moves. Also, it would be impossible to track ISP to a precision of a few hundred meters at 550 AU, as requested by the very tight alignement. By looking at the CMB, however, no more ISP tracking problem exist, since the CMB is almost uniformly scattered all over the celestial sphere. The CMB spectrum is perfectly blackbody with T=2.728 K, and peaks at 160.378 GHz. Thus the author could prove that the refractive effects of the Sun's Corona push the focus out to a distance of about 763 AU. This distance will be reached by ISP approximately in the year 2055. Under these conditions, the angular resolution on the CMB provided by the Sun's lens is a billion times better than COBE's! And "FOCAL" (an acronym for "Fast Outgoing Craft for Astrophysical Lensing"), will not just be looking at a point, but rather at a small line segment in the sky, enormously enlarged.

1. AN INTRODUCTION TO “SUNLENSING”

The focussing of light by the mass of the Sun is one of the most amazing effects predicted by general relativity. The first paper in this new research field was published by Einstein himself in 1936 (ref. 1), but his pioneering work remained forgotten for nearly three decades. The revival of interest only began in 1964, when Sydney Liebes of Stanford University (ref. 2) gave the mathematical theory of gravitational focussing by a galaxy located between the Earth and a very distant cosmological object like as a quasar. In 1974 Hans C. Ohanian investigated the lens gain (ref. 3), though he was chiefly interested to study the focussing of gravitational waves rather than of electromagnetic waves. Then, in 1975-76, a superb mathematical theory was given by the Jena mathematical physicists E. Herlt and H. Stephani (refs. 4 and 5), who solved the Einstein-Maxwell equations for the Spherical Gravitational Lens. In 1978 the first "twin quasar" image, caused by the gravitational field of an intermediate galaxy, was spotted by astronomer Dennis Walsh and his colleagues (ref. 6) and subsequent discoveries of several more examples of gravitational lenses eliminated all doubts about gravitational focussing predicted by general relativity. The next great step was taken in 1979 by Von Eshleman of Stanford University (ref. 7), who went on to apply the theory to the particular case of the Sun. His paper for the first time suggested the possibility of sending a spacecraft to 550 AU from the Sun to exploit the enormous magnifications provided by the gravitational lens of the Sun, particularly at microwave frequencies, such as the hydrogen line at 1420 MHz (21 cm wavelength). Nowdays, this is the frequency that all radioastronomers doing SETI (the Search for ExtraTerrestrial Intelligence) regard as the #1 "magic" frequency for interstellar communications, and thus the tremendous potential of the gravitational lens of the Sun for letting humankind get in touch with alien civilizations became obvious. The first experimental SETI radioastronomer in history, Frank Drake (*Project Ozma*, 1960), presented a paper on the advantages of using the gravitational lens of the Sun for SETI at the *Second International Bioastronomy Conference* held in Hungary in 1987 (ref. 8), as did Nathan "Chip" Cohen of Boston University (ref. 9). Non-technical descriptions of the topic were also given by them in their popular books (refs. 10 and 11).

However, the possibility of planning and funding a space mission to 550 AU to exploit the gravitational lens of the Sun immediately proved a difficult task. Space scientists and engineers first turned their attention to this goal at the June 18, 1992, *Conference on Space Missions and Astrodynamics* organized in Turin, Italy, led by the author of this note. The relevant Proceedings were published in 1994 in the *Journal of the British Interplanetary Society* (ref. 12). Meanwhile (May 20, 1993) the author submitted a formal Proposal to the European Space Agency (ESA) to fund the space mission design (ref. 13). The optimal direction of space to launch the FOCAL spacecraft was discussed by Jean Heidmann of Paris Meudon Observatory and the author (ref. 14) but, it seems clear that any mission to 550 AU should not be devoted entirely to SETI. The computation of the parallaxes of many distant stars in the Galaxy, the detection of gravitational waves by virtue of the very long baseline between the spacecraft and the Earth, and a host of other experiments would complement the SETI utilization of this space mission to 550 AU and beyond. The mission was dubbed "SETISAIL" in earlier papers (ref. 15), and "FOCAL" in the proposal submitted to ESA in 1993 (ref. 16). Finally, in 1997 the author published the first book devoted to the gravitational lens of the Sun and to the “FOCAL” space mission to 550 AU (ref. 17): this book was later awarded the 1999 Book Award by the International Academy of Astronautics (see the web site: http://www.iaanet.org/awards/book.html).

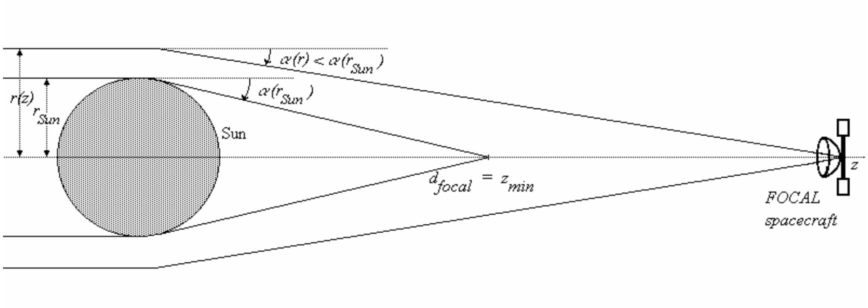

Fig. 1: "SunLensing" with minimal focal distance from the Sun and FOCAL spacecraft.

The geometry of the Sun gravitational lens (Figure 1) is easily described: incoming electromagnetic waves (arriving, for instance, from the center of the Galaxy) pass ***outside*** the Sun and pass, say, at a certain distance *r* of its center, (traditionally called impact parameter). Then, the well-known ***Schwarzschild solution*** to the Einstein equations shows that the minimal focal distance d_{focal} is

$$d_{focal} \approx \frac{r_{Sun}}{\alpha(r_{Sun})} = \frac{r_{Sun}}{\frac{4GM_{Sun}}{c^2 r_{Sun}}} = \frac{c^2 r_{Sun}^2}{4GM_{Sun}}. \tag{1.1}$$

Numerically, one finds

$$d_{focal} \cong 542\,\text{AU} \approx 550\,\text{AU} \approx 3.171\,\text{light days} \approx 14\ \text{times the Sun-to-Pluto distance}. \tag{1.2}$$

This is the minimal distance from the Sun that the FOCAL spacecraft must reach to get hugely magnified radio pictures of sources on the other side of Sun w.r.t. the spacecraft.

Furthermore, ***all points on the straight line beyond this minimal focal distance are foci too,*** because the light rays passing by the Sun further than the minimum distance have smaller deflection angles and thus come together at an even greater distance from the Sun. So***, it is not necessary to stop the spacecraft at 550 AU. It can go on to any distance beyond and focus as well or better.*** In fact, the further it goes beyond 550 AU the less distorted the collected radio waves by the Sun Corona fluctuations.

2. NASA's INTERSTELLAR PROBE (ISP) LONG FLIGHT: 2010 TO 2055…

The direction of the incoming interstellar wind is –16° in declination and +16.6 hours in right ascension. Toward this point NASA intends to launch its "InterStellar Probe" (ISP) in June 2010. This mission will go as far as possible away from the Sun. A 400-meters solar sail plus a suitable Sun flyby make the NASA planners expect that ISP will reach 250 AU from the Sun in just 15 years, i.e. around 2025. This distance is well beyond where the Heliosphere (the Sun-wind-dominated portion of space) ends with the Heliopause, and the Interstellar Space begins. Payloads aboard ISP will be devoted to study the Heliosphere, the Heliopause and the (possible) Bow Shock. However, the author of this paper suggested the ISP Team to put aboard ISP one more (small) instrument to perform an experiment called the "CBR SunLensing". This instrument could be either a photometer or a bolometer, or something similar. Essentially, its task is to observe the radiation emitted by some bright source (a quasar, a radiogalaxy or a bright star) and focussed upon ISP by the gravitational lens of the Sun.

ISP is expected to cross the sphere at 550 AU from the Sun around the year 2040, and this will thus be the first opportunity to check physically the magnifying properties of the Sun's gravity lens. Unfortunately the following two obstacles seem, in the first instance, to prevent this result from being achieved:

1) There is “nothing” (i.e. no quasar, or radioagalaxy, or bright star) on the celestial sphere in the direction opposite to the incoming interstellar wind direction, toward which ISP moves. In other words, no “bright electromagnetic source” is going to focus its flux upon ISP by virtue of the Sun's mass.
2) Even if we thought of correcting the ISP rectilinear trajectory so as to align it to a bright source, this would practically be impossible because ISP would have to be aligned with a tolerance of a few tens of meters, far beyond the tracking capabilities nowdays available for a spacecraft at 550 AU or beyond.

So we change the target.

3. LOOKING AT THE COSMIC MICROWAVE BACKGROUND THROUGH THE SUN'S GRAVITY LENS BY VIRTUE OF NASA'S INTERSTELLAR PROBE (ISP)

Rather than looking at quasars or bright stars and the like, we decide to look at the Cosmic Background Radiation (CBR) or Cosmic Microwave Background (CMB), the famous 2.728 °K blackbody radiation that has been filling the universe since the time of the decoupling between radiation and matter, about 300,000 years after the Big Bang. If we decide that ISP is going to look at the CBR through the Sun's gravity lens, then***, no more ISP tracking problem exist because the CBR is (almost) uniformly scattered all over the celestial sphere.***

It is interesting to compute the Gain (or magnification, i.e., in loose terms, the “focussing power”) provided by the Sun's Gravity Lens upon radiation of different frequencies. On the one hand, the Sun Gain alone is given by the formula (see ref. 2, page 11, for a discussion)

$$G_{Sun} = \frac{8\pi^2 \, G \, M_{Sun}}{c^2} \nu . \tag{3.1}$$

On the other hand, for a spacecraft having an antenna with radius $r_{antenna}$, the antenna Gain is (assuming 50% efficiency) is given by

$$G_{Antenna} = \frac{\pi \; r_{Antenna}^2}{2} . \tag{3.2}$$

From (3.1) and (3.2) it is concluded that the *total* Gain, namely the overall Gain of the combined system Sun+Spacecraft Antenna, is given by

$$G_{Total} = G_{Sun} \; G_{Antenna} = \frac{16\pi^4 \, GM_{Sun} \, r_{Antenna}^2}{c^5} \nu^3 . \tag{3.3}$$

NASA's ISP will have an antenna 2.7 meter in diameter. Replacing this value into (3.1), (3.2) and (3.3), one gets the following Table 1, showing the three Gains for the five selected frequencies listed hereafter:

1) The Neutral Hydrogen line (1420 MHz);
2) The Water Maser line (22 GHz);
3) The K_a band frequency (32 GHz), that will be used by NASA's ISP for the telecommunications with the Earth;
4) The peak of the 2.728 °K Cosmic Microwave Background (CMB) radiation (160.379 GHz);
5) The first line of the positronium (an "atom" made by a positron and an electron), at 203 GHz, that was suggested by Nikolai Kardashev in 1979 (see ref.) as the "best" line for SETI interstellar communications.

As one can see, the Total Gain falling upon NASA's ISP watching at the CMB through the Sun's Gravity Lens is huge: 148.03 dB.

Line	*Neutral Hydrogen*	H_2O	K_a*band*	CMB_{max}	*Positronium*
Frequency ν	**1.42 GHz**	**22 GHz**	**32 GHz**	**160.38 GHz**	**203 GHz**
Wavelength λ	21.112 cm	1.363 cm	9.37 mm	1.06 mm	1.48 mm
S/CAntenna Beamwidth	5.474 deg	0.353 deg	0.243 deg	0.049 deg	0.038 deg
Sun Gain	57.46 dB	69.36 dB	70.98 dB	77.96 dB	79.01 dB
2.7-m S/C Gain	29.07 dB	52.87 dB	56.13 dB	70.07 dB	72.17 dB
Combined Sun + S/C Gain	**86.53 dB**	**122.23 dB**	**127.11 dB**	**148.03 dB**	**151.18 dB**

Table 1: Gain (Magnification) of the Sun's Gravity Lens alone, the Gain of a 2.7-meter Spacecraft (S/C) Antenna and the Combined Gain of Sun+S/C Antenna System. Values for five frequencies hinted to be observed by NASA's Interstellar Probe (ISP).

4. A NINE ORDERS OF MAGNITUDE IMPROVEMENT ON COBE'S ANGULAR RESOLUTION BY LOOKING AT THE CMB THROUGH THE SUN'S GRAVITY LENS BY VIRTUE OF NASA'S ISP

The CMB (or CBR, or Cosmic Infrared Background) is integrated light from all stars and galaxies that cannot be resolved into individual objects. So it is meaningless to speak of "angular resolution" for the Sun's Gravity Lens when the latter is used to watch at the CMB (whereas, of course, the term "angular resolution" retains the usual meaning when watching at stars, planets, even black holes, through the Sun's Gravity Lens). Calculations made by this authors that cannot be reported here indicate that the improvement in the (theoretical) angular resolution of the CMB as watched through the Sun's Gravity Lens, rather than through COBE, is about nine order of magnitude. See Table 2.

Line	*Neutral Hydrogen*	H_2O	K_a *band*	CMB_{max}	*Positronium*

Frequency ν	**1.42 GHz**	**22 GHz**	**32 GHz**	**160.38 GHz**	**203.38 GHz**
Wavelength λ	21.112 cm	1.363 cm	9.37 mm	1.06 mm	1.48 mm
Angular Resolution at 550 AU	$6.3458\ 10^{-6}$ arcsec	$4.0959\ 10^{-7}$ arcsec	$2.8159\ 10^{-7}$ arcsec	$5.6584\ 10^{-8}$ arcsec	$4.4389\ 10^{-8}$ arcsec
Angular Resolution at 800 AU	$5.2267\ 10^{-6}$ arcsec	$3.3736\ 10^{-7}$ arcsec	$2.3194\ 10^{-7}$ arcsec	$4.6606\ 10^{-8}$ arcsec	$3.6561\ 10^{-8}$ arcsec
Angular Resolution at 1000 AU	$4.6749\ 10^{-6}$ arcsec	$3.0174\ 10^{-7}$ arcsec	$2.0745\ 10^{-7}$ arcsec	$4.1685\ 10^{-8}$ arcsec	$3.2701\ 10^{-8}$ arcsec

Table 2: Angular Resolution provided by the Sun's Gravity Lens for NASA's Interstellar Probe (ISP), having a a 2.7-meter antenna. Values for the five selected frequencies.

In the NASA's ISP Booklet (1999, ref. 17, page 14) one reads: "NASA's Cosmic Background Explorer (COBE, launched in 1989; its results were published in 1993) detected the cosmic infrared background at wavelengths beyond 140 microns and established limits on the energy released by all stars since the beginning of time. Also, by observing the cosmic infrared background it is possible to determine how much energy was converted into photons during the evolution of galaxies, back to the time of their formation. Fundamental measurements about galaxy formation can be made even though individual protogalaxies cannot be seen. The cosmic infrared background spectrum can reveal how first stars formed and how early the elements were formed by nucleosynthesis".

Perhaps "virtual" angular resolution data given in Table 2 above have a deeper significance that escapes us at this time. Understanding better what "watching at the CMB through the Sun's Gravity Lens means" is a current research problem.

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