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 requirements for an instrumented spacecraft to reach regions beyond the minimum focal distance of the gravitational lens of the sun, as explained below. The lens itself might then be employed by the spacecraft to (i) detect and study characteristics of planets orbiting a preselected target star; (ii) eavesdrop for technological activity on a favorable planet in that stellar system, as might be manifested by coherent radiation at millimetric and shorter wavelengths; and (iii) support the eventual establishment and maintenance of two-way communications with an identified technical society. While the potential of the lens effect appears substantial, it is evident that the problems attending its use would be formidable. The following discussion is offered in the context of other complementary and alternative suggestions concerning the search for extraterrestrial intelligence and the establishment of interstellar communications (*2*), where aspects of these suggestions may be comparably speculative and tentative.

Consider the focusing of coherent radiation from a distant point source by a spherical gravitational field. In Fig. 1, a plane wave of unit intensity is assumed incident from the left into the gravitational field, whose relativistic effect can be represented by the refractive index $1 + \nu$, where the refractivity $\nu = g/r$ at radius r. A ray is deflected through the angle $\alpha = 2g/a$, where a is the ray impact parameter and g is the gravitational radius ($g = 2Gm/c^2$, where G is the gravitational constant, m is the mass of the central body, and c is the speed of light). It is assumed throughout that $\alpha << 1$. An observer at position z behind the lens and x from the center line, as illustrated, would see an energy density lessened by defocusing in the plane of propagation, but increased by focusing due to the curved limb normal to this plane. The relative single-ray intensity $I = F_h^2 F_v^2$, where in ray optics $F_h^2 = a/x$ and $F_v^2 = (1 - z d\alpha/da)^{-1}$. It follows that

$$I = \frac{1}{2}\left[\frac{X^2 + 2}{X(X^2 + 4)^{1/2}} \pm 1\right] \qquad (1)$$

where $X^2 \equiv x^2/2gz$. Equation 1 is plotted in Fig. 2, where the upper and lower signs apply for a and x on the same (near-limb ray) and opposite (far-limb ray) sides of the center line, respectively. As $x \rightarrow 0$, the two signals become of comparable strength and the sum intensity would oscillate between a low of $X/2$ and a high of $2/X$, with an average of $1/X$. The singularity at $x = 0$ requires further consideration. At the focus, $F_v^2 = 1/2$ and $F_h^2 = 4\pi^2 a^2/\lambda z$ in wave optics (*3*), where λ is the radiation wavelength, so that F_h is the number of free-space Fresnel 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

$$I_{\max} = 2\pi\, kg \qquad (2)$$

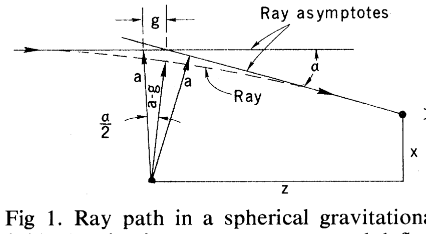

Fig 1. Ray path in a spherical gravitational field, showing impact parameter a and deflection angle α for a field characterized by the gravitational radius g, where $\alpha = 2g/a$ and the minimum distance of the ray from the center of mass is $a - g$.

As an approximation, let the focal "spot" radius x_s be the value of x where I falls to $I_{\max}/4$, so that $x_s = (2/\pi k)(z/2g)^{1/2}$. Thus the angular resolution for distinguishing two adjacent coherent sources by a corresponding change in intensity is x_s/z radians. (The first null off the center line is at $x = \pi^2 x_s/2$, and the first sidelobe is twice this distance with intensity $I_{\max}/\pi^2$.) The periapsis 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 $\alpha_{\max} = 2g/r_0$ and the focal line begins at $z_{\min} = r_0^2/2g$.

Now consider the focusing at $z > z_{\min}$ of incoherent radiation from a uniformly bright, circular, extended source of radius r_p and distance $z_p >> z$. 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 (as compared with the intensity for the unaltered image) is essentially the same as the two corresponding values of I in Eq. 1. These components would consist of two distorted elliptical images at the near and far limbs defined by the two ray periapses. For perfect alignment ($x = 0$), the two images would merge into an annulus of angular radius $\theta_0 = (2g/z)^{1/2}$ and width $\phi_0 = r_p/z_p$. Thus, as shown by Liebes (*4*)

$$A_{\max} = 2\theta_0/\phi_0 = (2z_p/r_p)(2g/z)^{1/2} \qquad (3)$$

In the sense of the definition of x_s, the spot radius for this central peak is $r_p z/z_p$.

For the sun, $g = 2955$ m and $r_0 = 6.96 \times 10^8$ m, so $z_{\min} = 8.19 \times 10^{13}$ m, or about 3 light-days or 550 astronomical units (1 AU is the average sun-earth distance). For illustration, assume $z = 4z_{\min}$ and $\lambda = 10^{-3}$ m so that $a = 2r_0$, $x_s \cong 24$ m, and $I_{\max} \cong 10^8$ for a coherent point source, neglecting the coronal effects discussed below. Using an earth-sized planet at $z_p = 20$ light-years as an example of an incoherent extended source viewed at the same z, its focused annular image would have an angular radius of 0.88 arc sec, or twice the solar disk value, and an angular strip width of 6.9×10^{-6} arc sec, with a spot radius of

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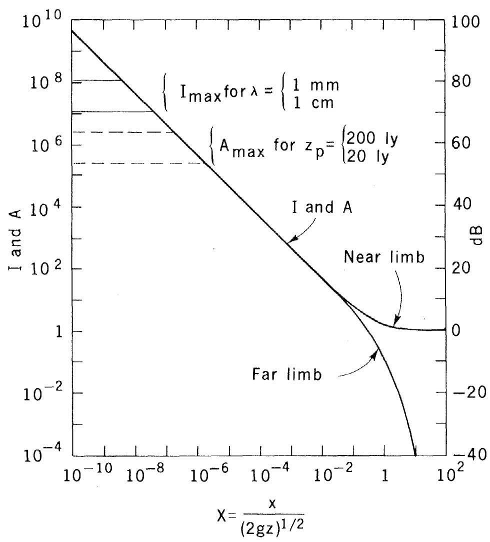

Fig. 2. Intensity magnification factors for the near- and far-limb images in a gravitational lens, for coherent (I) and incoherent (A) sources, plotted as a normalized function of the distance of the receiver from the focal axis. Also shown are wave-optical maximum values of I for the solar lens at the indicated wavelengths (neglecting the corona), and maximum values of A for a planet the size of the earth at the indicated distances, as viewed through the solar lens from a distance four times its minimum focal length. Abbreviation: *ly*, light-years.

11 km and $A_{max} \cong 2.5 \times 10^5$. These and additional values of I_{max} and A_{max} are illustrated in Fig. 2, where the normalized spot radii would correspond to four times the abscissa of the intersection of the I_{max} and I or A_{max} and A lines. The spatial resolution for distant coherent sources is $x_s z_p / z$, or 14 km in the example above.

Several of the problems characterized above as formidable are evident as such from the preceding paragraph. The great potential is also obvious. The I_{max} example, if realizable, means that with current spacecraft and communications technology for very short wavelengths, we could detect coherent sources and communicate over interstellar distances within a neighborhood of thousands of stars, with sensitivities and data rates comparable with the capability attained a decade ago for spacecraft communicating over interplanetary distances. A particular communication capability on the local link, perhaps between near-earth orbit (to avoid atmospheric attenuation) and the spacecraft at 2200 AU, would also be possible with identical terminal equipment over a path length of about 350 light-years, if an I_{max} of 10^8 were achieved (*5*).

In addition, the attainment of A_{max} and substantial angular and spectral discrimination against the solar and stellar signals might make it possible to detect natural radiation from earth-like planets at the distances of the nearer stars, to aid in the identification of likely targets for eavesdropping. Major difficulties would be encountered in placing spacecraft at the requisite distance from the solar lens and in finding and tracking positions of interest relative to the very small spot sizes. In this regard, it is obvious that a single spacecraft using the solar-lens approach is suited for searches only over extremely small ranges of angles, such as within a specific stellar system identified by other techniques as being of special interest. Other concerns are the effects of the solar corona and the lack of perfect sphericity of the solar lens.

To reach 2200 AU in, say, 50 years means a spacecraft speed of about 200 km/sec. Here again the solar "focus" can help, since it requires less propulsive fuel to go in a given time from orbit within a gravitational field to a point well outside than to go directly between two similarly separated outside points, if the spacecraft first falls very close to the center of the field so that a large impulse can be applied at very high velocities. Low, continuous thrust techniques might also be usefully employed during the cruise. One might be concerned that while the sun can help at the start, there is no comparable way to stop at any particular z. But it would be better to continue since I_{max} is independent of z while coronal effects would be reduced as z increases (*6*). Also, A_{max} varies as $z^{-1/2}$ while the competing solar signal varies as z^{-2}. Although it may at first appear virtually impossible to find a spot size with a radius of 24 m, as in the 1-mm λ example, note that the detectable size grows linearly with signal strength. For example, a coherent source would be seen over a 24-km radius if $10^{-3}\, I_{max}$ gave a detectable signal.

The effects of the oblateness of the sun and hence of its gravitational field can be treated in a manner analogous to focusing by the atmosphere of an oblate planet (*3*). For the focal zone in the equatorial plane of the oblate sun

$$I_{max}(\text{oblate}) \cong (2/\epsilon)^{1/2}\,(kg/2\pi)^{3/4} \qquad (4)$$

for values of the gravitational field oblateness ϵ that make Eq. 4 less than Eq. 2. The mass quadrapole parameter J_2 for the sun is not known but its upper limit is about 3×10^{-6}, so that ϵ is less than 10^{-6} at $a = 2r_0$, for example. Thus it does not appear likely that solar oblateness will affect I_{max} by a substantial amount from radio to light wavelengths, while the effect on A_{max} would normally be even less. (Conversely, measurement of a coherent spot size and shape might provide a very sensitive determination of J_2.) Even if the sun were perfectly spherical, its equivalent refractivity field due to gravitation would be distorted by the relativistic mass-current effect associated with solar rotation, but here again this would not noticeably degrade its focusing characteristics.

The corona of the sun constitutes a serious limitation to the use of the lens effect at radio frequencies. Average coronal gradients deflect a ray outward by an amount approximately proportional to λ^2/a^6. For example, this effect would cancel the gravitational deflection at $a = 2r_0$ for a wavelength of about 3 cm, and at $a = 4r_0$ for about 15 cm. In addition, coronal asymmetries and turbulence would act to destroy the coherence needed to achieve the idealized values of I_{max}. Moving to shorter λ and larger z would markedly reduce the coronal effects, but it is clear that the use of the solar lens, for values of z/z_{min} that are not exceptionally large, will be restricted to wavelengths shorter than the order of 1 cm in any application, and perhaps several orders of magnitude less when some degree of coherence is required (*6, 7*). While the potential of the technique for communications and for observing thermal sources need not be compromised by this limitation, the eavesdropping mode might be of relatively limited value if we take an anthropocentric view of the characteristics of possible technological sources, or consider the much longer neutral hydrogen or "water-hole" wavelengths to be signposts marking likely values for interstellar communications (*2*). On the other hand, the terrestrial trend has been toward the use of shorter and shorter wavelengths for various applications, and the concept of the utility of stellar gravitational lenses, if similar to the sun's, might be a universally recognized signpost arguing for the use of shorter characteristic wavelengths for attempting first contacts and for subsequent communications. For example, a common heritage through carbon- and water-based life might be indicated by use of a spectral association with the millimetric lines of the HCO or formyl radical.

It has been pointed out that radio, television, radar, microwave link, and other terrestrial transmissions are expanding into space at 1 light-year per year (*2*). Another technological society near a neighboring star could receive the strongest of these directly with substantial effort and could learn a great deal about the earth and the technology of its inhabitants. The concepts presented here suggest that on an imaginary screen sufficiently far behind that star, the short-wavelength end of this terrestrial activity is now being played out at substantial amplifications. Properly placed receivers with antennas of modest size could in principle scan the earth and discriminate between different sources, mapping such activity over the earth and learning not only about the technology of its inhabitants, but also about their thoughts. It is possible that several or many such focused stories about other worlds are now running their course on such a gigantic screen surrounding our sun, but no one in this theater is observing them (*8*).

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References and Notes

1. A. Einstein, *Science* **84**, 506 (1936).
2. For example, see G. Cocconi and P. Morrison, *Nature (London)* **184**, 844 (1959); I. S. Shklovskii and C. Sagan, *Intelligent Life in the Universe* (Holden-Day, San Francisco, 1965); A. G. W. Cameron, Ed., *Interstellar Communication* (Benjamin, New York, 1963); C. Sagan and F. Drake, *Sci. Am.* **237**, 80 (May 1975); B. M. Oliver and J. Billingham, "Project Cyclops: A design study of a system for detecting extraterrestrial intelligent life," *NASA Contract Rep. CR114445* (1973); W. T. Sullivan III, S. Brown, C. Wetherill, *Science* **199**, 377 (1978); B. Murray, S. Gulkis, R. E. Edelson, *ibid.*, p. 485; R. N. Bracewell, *The Galactic Club* (Freeman, San Francisco, 1974). The messenger probe concept introduced by Bracewell would require communications to a home base over interstellar distances. Thus a gravitational lens could have application here, and also in astronomical observations of the more usual type.
3. V. R. Eshleman, G. L. Tyler, W. T. Freeman, *Icarus* **37**, 612 (1979).
4. S. Liebes, Jr., *Phys. Rev.* **133**, B835 (1964).
5. There are some interesting questions about how a two-way exchange might be initiated and maintained with a single lens used for both directions, since the paths are so directive that separated transmitting and receiving locations would be required on at least one end of the path. Perhaps a symmetrical situation would be preferable, where a lens at each end would be used but only for reception, with transmissions originating from the respective home planets. Of course, in all cases the local links would involve two-way communications.
6. By traveling this far along a radius from the sun, it would be possible to use most of the nearer stars as lenses to observe regions along a very narrow angular strip within a few tenths of a degree from the directions of these stars as viewed from the earth. However, it would not be possible to dwell on a particular direction or come back to a previous one without a large change in the spacecraft velocity. If the lens of a nearby star that is similar to the sun were used, the large value of z would mean that coronal effects would be reduced considerably.
7. Using the example of $z = 4z_{min}$, a wavelength of less than 1 or 2 cm is needed for energy to even reach the focal zone. Coronal irregularities would break up the principal Fresnel zone annulus of the idealized coherent case into a large number of incoherent smaller zones for wavelengths from these values to several orders of magnitude smaller, with the number of pieces decreasing as the wavelength is reduced. The maximum value of the average signal intensification would still be appreciable, varying inversely with the number of zones. Thus, while our idealized example of $I_{max} \cong 10^8$ at $\lambda = 10^{-3}$ m and $z = 4z_{min}$ would not be realized, this value of I_{max} might be obtained at a somewhat shorter wavelength.
8. As an extension of the conclusions of Einstein (*1*) and Liebes (*4*) concerning the improbability of observing the flash of two suitably aligned stars, it is interesting that if there were a technological society orbiting each visible star in our galaxy, and if every one of them were communicating with every other one except ours by use of stellar gravitational lenses (quintillions of paths), it is highly unlikely that the earth, by chance, would have intercepted any of the focal lines since the time when we first developed radio receivers.
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Enhanced 5-Fluorouracil Nucleotide Formation After Methotrexate Administration: Explanation for Drug Synergism

Abstract. *Exposure of L1210 leukemia cells first to 0.1 to 100 micromolar methotrexate and then to 10 micromolar 5-fluorouracil produces a synergistic effect on the number of cells killed in culture. Methotrexate dose-related increases occur in the concentrations of intracellular 5-fluorouracil ribonucleotides and 5-fluoro-2′-deoxyuridylate and in the incorporation of 5-fluorouracil into RNA. These increases are correlated with increased concentrations of intracellular phosphoribosylpyrophosphate. It is proposed that the enhanced formation of ribonucleotides of 5-fluorouracil and the subsequent incorporation of these compounds into RNA in methotrexate-treated cells may account for synergism between these agents.*

Methotrexate (MTX) and 5-fluorouracil (5-FU) are often used in combination for the treatment of breast cancer (*1*). However, recent biochemical studies demonstrating antagonism of MTX and 5-FU with thymidylate synthetase question the rationale for concurrent use of these chemotherapeutic drugs (*2, 3*). Inactivation of thymidylate synthetase by 5-fluoro-2′-deoxyuridylate (FdUMP) requires the formation of a ternary complex among FdUMP, 5,10-methylenetetrahydrofolate (CH_2FAH_4), and thymidylate synthetase, leading to the covalent binding of FdUMP to this enzyme (*4–6*). By inhibiting dihydrofolate reductase, MTX prevents regeneration of CH_2FAH_4 from the oxidized folate (FAH_2) formed during thymidylate synthesis. It is this depletion of CH_2FAH_4 that has been proposed (*3*) as a basis for the biochemical antagonism observed in vitro when MTX is administered before 5-FU. Since MTX is only 21 percent as efficient as CH_2FAH_4 in promoting the binding of FdUMP to thymidylate synthetase (*7*), and possibly does not permit the covalent association of FdUMP with this enzyme, it is unlikely that a direct interaction between MTX and thymidylate synthetase can compensate for the reduced concentrations of CH_2FAH_4. Methotrexate also increases intracellular deoxyuridylate (dUMP) (*8, 9*), which

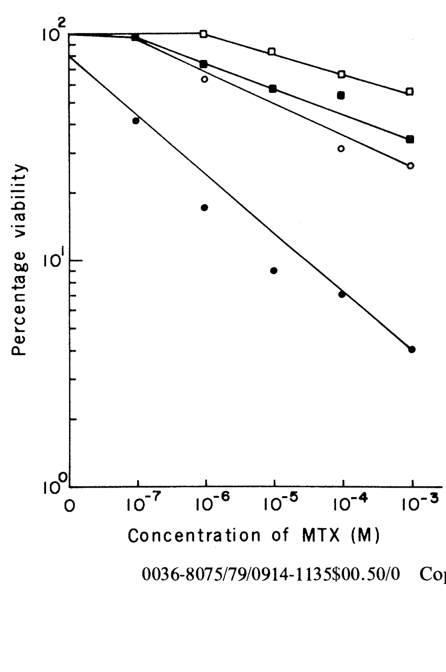

Fig. 1. Soft agar cloning of L1210 cells. The L1210 cells in Fischer's medium were exposed to MTX at the indicated concentrations for 2 or 4 hours. The drug-containing medium was then removed and the cells were washed twice with drug-free medium before cloning. Symbols: □, cell viability after 2 hours, and ■, after 4 hours of exposure to MTX. The MTX at the designated concentrations was present in the medium for 3 hours before 1 μM (○) or 10 μM (●) 5-FU was added for 1 hour. The cells were then cloned in drug-free medium. This sequence increased the number of cells that were killed, with 10 μM of 5-FU having the greatest effect. The viability of cells exposed to either dose of 5-FU alone for 1 hour was 100 percent of the no-drug control. Cloning efficiency was 90 percent. Cell viability was determined from the number of clones formed from drug-treated cells divided by the number of clones formed from control cells multiplied by 100.

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