

A NEUTRINO BEACON

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Observational SETI has concentrated on using electromagnetism as the carrier, namely radio waves and laser radiation. Michael Hippke [2] has pointed out that it may be possible to use neutrinos or gravitational waves as signals. Gravitational waves demand the command of the generation of very large amounts of energy, Jackson and Benford [3]. This paper describes a beacon that uses beamed neutrinos as a carrier for a signal. Neutrinos, like gravitational waves, have the advantage of extremely low extinction in the interstellar medium. To make use of neutrinos an advanced civilization can use a gravitational lens as an amplifier. The gravitational lens can be a neutron star or a black hole. Using wave optics one can calculate the advantage of gravitational lensing for amplification of a beam and along the focal axis, it is exceptionally large. Even though the amplification is very large the diameter of the beam is quite small, less than a centimeter. This implies that a large constellation of neutrino transmitters would have to enclose a local neutron star or black hole lens to make an approximate isotropic radiator. The operational energy needed is about .01 Solar, this means that such a beacon would have to be built by a Kardashev Type II civilization.

Keywords: Neutrinos, Gravitational Lens, SETI

1 INTRODUCTION

The Search for Extra-Terrestrial Intelligence has been an active endeavor for over 50 years. These searches have focused on using photons in the infra-red, microwave and radio-frequencies. These ideas spawned concepts that advanced civilizations might build beacons. Recently thoughts about the spectrum of long range carriers have been extended to neutrinos and gravitational waves, Hippke (2018) [2].

Gravitational waves as a signal beacon has been presented by Jackson and Benford [3]. Over cosmic distances directed gravitational waves are very expensive in energy, demanding a command of levels of energies above Kardashev III civilizations [4].

Pasachoff and Kutner[5], Learned, et al.[6] and Pakvasa

This paper was inspired by the Technosignatures Workshop in September 2018 [28]..

[7] have presented ideas about using neutrinos for interstellar communication. Advantages of using neutrinos are: (1) neutrinos arrive almost without attenuation from any source direction, which is a big advantage in the Galactic plane; (2) neutrinos, at the Earth, are rare in certain energy ranges, and from a given direction are all but negligible; (3) even when photons are not completely blocked, their scattering introduces jitter in arrival time as well as direction [6].

Herein is presented a method for using a gravitational lens to amplify the effectiveness of a neutrino beam transmitted across interstellar distances.

2 GRAVITATIONAL LENSING

Gravitational lensing has been proposed as a means of enhanced interstellar communication, *see* Eshleman (1979)[8], or Maccone for an extensive treatment [9]. Consider a K2 civilization using a Schwarzschild or Kerr black hole as a means of focusing radiation from a beaming station. The advantage

TABLE 1: Long range zero and near zero rest mass messengers (after Hippke[2])

Carrier	Rest Mass (MeV/c ²) / Speed	Lifetime	Extinction	Sources
Photons	0 $v = 1$	Stable	.001	Beacons, Deliberate Transmissions, Propulsion Stations, Ambient Radiation from Star Ships, Waste Heat Star Ships, Waste Heat ("Dyson Spheres"), A large "Instrumentality"
Neutrinos	$\sim .001$ $v \sim 1$	Oscillations Stable	~ 0	From Star Ship, A Beacon, Deliberate Beaming for Communication
Gravitons Gravitational Waves	0 $v=1$	Stable	~ 0	A very advanced civilization's beacon

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = (1 - \frac{r_s}{r}) dt^2 - (1 - \frac{r_s}{r})^{-1} dr^2 - r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \quad (1)$$

of this is the enormous amount of amplification possible. Any gravitating body may serve as a lens – an ordinary star, a neutron star or a black hole [10].

It is known that focusing of light by a gravitating point mass leads to caustic focal structures and that a geometrical optics treatment gives an infinite gain of the focused radiation on the optical axis [11]. The optical axis is the line connecting the source, lens and observer; we are interested in the case where the source is behind the lens and there is an observer at the caustic crossing. In a wave optics treatment, the gain on the caustic is not infinite but very large as was shown by Bliokh and Minakov (1975) [12]. We want to emphasize the observable amplification at the caustic crossing, thus some elaboration of the calculation is in order. Given here is a sketch of the derivation.

Gain is defined as the ratio of the scattered flux per unit solid angle (at a large distance from the scattering center) to incident radiation flux. The proper calculation of the gain on the optical axis must take diffraction into account. This can be done in two ways – by solving the wave equation as a scattering problem for the scalar case with the proper boundary conditions [13], or by using the Fresnel–Kirchhoff phase integral [11]. Take the case of solving the wave equation. The space-time of a black hole can be described by the Schwarzschild metric [11] in Eq. (1) above, where r , θ and ϕ are spherical coordinates and t is the coordinate time, with M the mass of the black hole. If G is a gravitational constant and c the speed of light, then

$$r_s = \frac{2GM}{c^2} \quad (2)$$

is the Schwarzschild radius.

Write the propagation of a plane wave on the Schwarzschild background and use the Fourier decomposition for the angular parts [11]:

$$\varphi(x^\mu) = \frac{1}{4\pi r} \sum_l \sum_m e^{-i\omega t} Y_l^m(\theta, \phi) \Psi_{lm}(\omega, r) \quad (3)$$

where Y_n^m are the spherical harmonics and Ψ solves the radial wave equation of a scalar field

$$\nabla^2 \Psi + (\omega^2 + \frac{2\omega^2 r_s}{r}) \Psi = 0, \quad (4)$$

that is, the wave equation of scalar radiation of frequency ω and wave function Ψ .

If (4) is subject to boundary conditions that define the incoming and scattered wave

$$\Psi = e^{ikz}(in) + f(\theta) \frac{e^{ikr}}{r} (scattered) \quad (5)$$

Then the solution, in cylindrical coordinates, is [12, 13, 14, 15, 16, 17, and 18]:

$$\Psi = e^{\frac{\pi\omega r_s}{2}} \Gamma(1 - i\omega \frac{r_s}{2}) {}_1F_1(i\omega \frac{r_s}{2}, 1; i\omega(r-z)) e^{i\omega z} \quad (6)$$

Where ${}_1F_1$ is a confluent hypergeometric function and r , θ and

z are cylindrical coordinates.

In the high frequency limit $\omega \rightarrow \infty$ and first order gravitational field, the wave function (2) and the incoming intensity I_0 define the gain [18]:

$$gain = \frac{\Psi \Psi^*}{I_0} \quad (7)$$

And Ψ in this limit (6), close to the focal line in the image plane leads to [18]:

$$gain_0 = \frac{4\pi^2 r_s}{\lambda} J_0^2(2\pi \frac{\rho}{\lambda} \sqrt{\frac{2r_s}{z}}) \quad (8)$$

where J_0 is the first order Bessel function. The first term is the scaling, proportional to the Schwarzschild radius divided by the wavelength. The Bessel function term is oscillating and due to interference averages to $\frac{1}{2}$. The second term also defines the spatial extent to a ‘focal beam’ (a caustic on the focal line, this term is sometimes called the Point Spread Function, PSF). A very exhaustive treatment of this lensing problem for the wave optics electromagnetic case is given by Turyshev and Toth 2017, [18].

In this wave optics solution it was noted that there are three regions – a shadow, a region of geometric optics and on the focal line a beam of large intensity due to diffraction (Fig. 1). From (4) plots can be made of the PSF as a function of ρ and z . There is a prime focal point at $z_0 = R_n^2/2r_s$, and z down the axis can be written as:

$$z(b) = z_0(b^2/R_n^2) \quad (9)$$

where b is the impact parameter of a neutrino ray and R_n is the neutron star radius.

Fix z at z_0 then in the image plane perpendicular to this point in normalized units the spread is given in Figure 1.

If ρ is fixed and z allowed to increase down the focal axis, the PSF becomes asymptotic in a few multiples of the prime focal point (see Fig. 2).

Then this implies that the central peak in Figure 1 broadens and most of the flux falls in a region defined by the zeros of the Bessel function.

For a stellar mass gravitational lens and 1 GeV neutrinos, the wavelength is about 10^{-14} cm, and the gain is approximately 10^{20} ! The characteristic radius of the main region of concentration is about one micron; however there is an effective flux out to about one centimeter. This beam intensity extends to very long distances, is only diminished by absorption in the interstellar medium or by encounters with a massive object like a planet or star, and has a very small beam divergence.

The usual treatment for the above diffraction model is for a telescope. Of interest here is a transmitter – that is, forward scattering used to propagate a beam of high concentration.

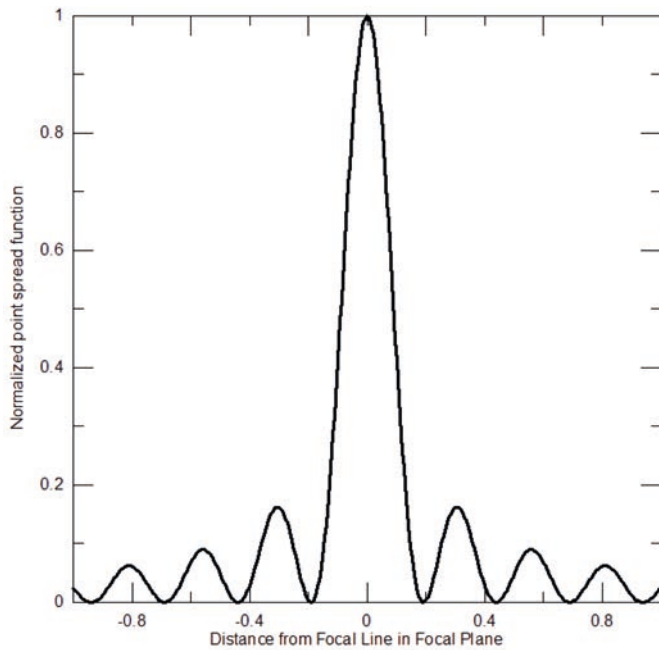


Fig.1 The normalized point spread, PSF, for a gravitational lens.

3.0 TRANSMISSION AND DETECTION

How might an advanced civilization configure an artifact to exploit the model described in Section 2? The gravitation lens could be a neutron star (a neutron star is very spherical), a black hole (a non-rotating black hole is spherical), or an ordinary star (although other condensed stellar objects are not considered here). Consider a neutron star with a neutrino beam transmitting station in orbit about it. At present, a typical high-energy neutrino beam is made from the decay of π mesons. Large accelerators boost particles, usually protons, to relativistic energies that strike a target which produces pions and kaons that decay in flight into neutrinos, electrons and muons. The useful feature is that the pions and kaons can be focused and a directed beam of neutrinos produced. These neutrinos will emerge from the source into beam angle θ determined by Special Relativity, that is:

$$\theta = \frac{1}{\gamma} \quad (10)$$

Where γ is the Lorentz factor $\frac{1}{\sqrt{1-\beta^2}}$

(β =speed as a fraction of light speed).

Taking the gravitational lens to be a neutron star or a non-rotating stellar mass black hole, a transmitter is envisioned (a rotating black hole, a Kerr black hole, could also be used, but the modeling is more complicated and is not considered here). Place a neutrino beam transmitter at 100 neutron star radii or at about 1000 km and using an impact parameter of 25 radii, the opening angle (by simple geometry) will be approximately 1 degree. This gives a Lorentz factor of 74, which results in a pion bunch with an energy of about 8 GeV. Thus there is a beam of approximately 8 GeV neutrinos incident on an annulus with a width of 15 km. Suppose the energy input is one watt for one second, then 8×10^{14} neutrinos flow into an area of about $8 \times 10^{11} \text{ m}^2$, which in turn is focused into an area of approximately 1 cm^2 resulting in a bolt of GeV neutrinos. A 1.4 solar mass

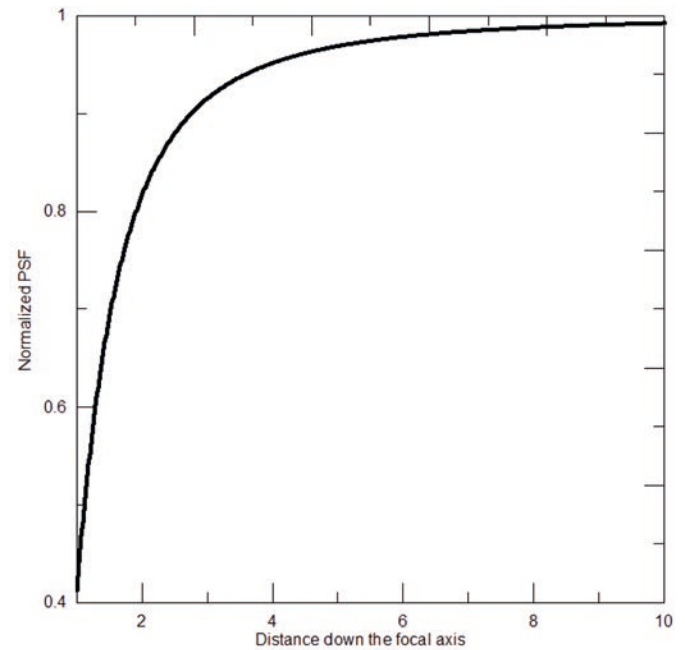


Fig.2 The PSF as a function of distance down the focal axis for a fixed ρ .

neutron star has a Schwarzschild radius of about 3 kilometers and 8 GeV neutrinos have a wavelength of about 10^{-14} cm (10^{-4} picometres), thus the gain from (8) – or amplification – from the gravitational lens is about 10^{21} on the focal axis. On the focal axis in the center of the ‘bolt’ is a one cm spot with approximately 10^{20} neutrinos per pulse.

Define the resolution of the neutron star beacon by the location of the first null of the Bessel function argument in (8) or the first zero in Figure 1, then the ‘spot’ in the image plane is associated with the angle $\theta_s = \rho/z$, where ρ is the ‘radius’ of a spot at a transmitter distance of z . To emphasize take as the region of interest the distance to the first null of the Bessel function, equation (8):

$$J_0^2(2\pi \frac{\rho}{\lambda} \sqrt{\frac{2r_s}{z}}) = 0 \quad (11)$$

The first null is $r_n = 2.40483$, then (10) can be solved for θ , [17]:

$$\theta_s = \frac{r_n \lambda}{2\pi b} \quad (12)$$

The radius of the spot at the detection distance is $\rho = \theta_s z_t$, where z_t is the distance from transmitter to the target. Here is a problem similar to the ‘resolution’ of an image by a gravitational lens except the detector is a neutrino telescope.

The dependence in (11) is only on two independent parameters – wavelength and impact parameter b . With the transmitter at 100 neutron star radii and the maximum impact parameter set at 25 neutron star radii, the resulting neutrino energy (9) means with a wavelength of 10^{-14} cm , resulting in a very small angle – $\theta_s = 2.4 \times 10^{-22}$ radians.

As an example, take the characteristic distance of an advanced civilization in our galaxy to be $z_t = 10,000$ light years, then ρ is approximately 2 centimeters!

If the transmitter pulses at a rate of one second then the ‘bolt’ of neutrinos moves off to infinity at almost the speed of

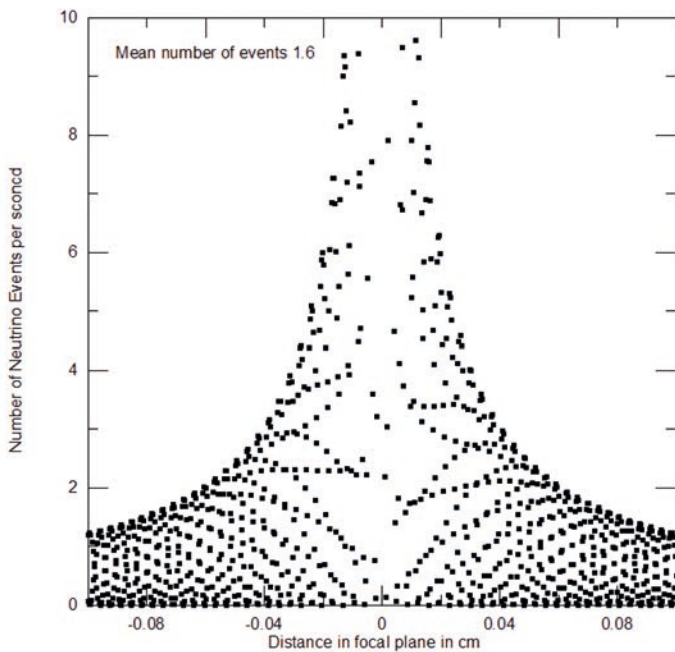


Fig.3 Neutrino events in a candidate neutrino water detector.

light and is only attenuated when it strikes a mass. Suppose it encounters a neutrino ‘detector’, then to estimate the number of scattering events in a cylinder of water 1 meter long and 1 meter in diameter:

$$N_{events} = \frac{\sigma N_m \rho_w N_{av}}{A} \quad (13)$$

Where σ is the interaction cross section for 8 GeV neutrinos, which is approximately 10^{-42} m^2 (10^{-38} cm^2) [19], N_m is the number of neutrinos passing in per unit time, ρ_w is the density of water, N_{av} is Avogadro’s number and A is the atomic number of water. Even though the cross section is extremely small, approximately an average of 2 events are seen per second in a cylinder approximately one cm in diameter. Figure 3 shows only the peak of detections in an area with a radius of about 0.1 cm in the detector for a single beam intersection of a detector. The configuration here is extremely idealized and there are a number of parameters subject to errors, but this would be a lot of detections, even if it was only one per hour. IceCube [20] detects about 11 neutrinos a day.

It is of note that one might make the beam cross section larger since the size goes approximately as $\sim \text{wavelength}/\text{Schwarzschild radius}$. However since the absorption cross section for neutrinos on baryons depends on energy, the shortest wavelength is desired. One might look for small primordial black holes (much less than a solar mass) as lenses, but those remain speculative at the moment. The model described above results in a very small ‘spot’ for detection but it is a consequence of the physics.

4.0 THE BEACON

An extreme problem presents itself; a one centimeter beam aimed over 10,000 light-years has an almost zero probability of intersecting a detector on the Earth. A simple estimate of the probability of a detection is $\theta s/4\pi$, in this case approximately 10^{-21} . One could extrapolate that a Kardashev 2 (K2) civilization can construct the pointing accuracy of an ultra-advanced mechanism to aim an almost infinitively sharp beam at a target

over thousands of light years with accuracy, but that will be left as a thought.

One can make another extrapolation: if the number of transmitters is increased to make the transmitter more isotropic-like, it could make detection easier by increasing the probability of seeing a single beam. Suppose that a K2 type civilization capable of interstellar flight can reach a neutron star or black hole, it should have the technological capability to build a beacon consisting of an array of transmitters in a constellation of orbits about the neutron star. Let this constellation consist of 10^{18} ‘neutrino’ transmitters 1 meter in characteristic size ‘covering’ the area of a sphere 1000 km in radius with 10^{18} particle accelerators in orbit (Figure 4). At the present time there is the development of plasma Wakefield particle accelerators that are meters in size [21, 22]. It is probable that a K2 civilization may construct Wakefield electron accelerators of very small size.

We will also suppose that a K2 civilization can solve all the problems of pointing errors and jitter, which could be substantial, and that the engineering physics is orders of magnitude beyond any our current civilization is capable of. Also, the engineering physics involved in guidance, navigation and control of a constellation of 10^{18} small spacecraft will be extremely complicated.

To summarize, the engineering physics approach would be to build a constellation of neutrino beam transmitters. Place, in orbit, at 100 neutron star radii, 10^{18} advanced small Wakefield accelerators one meter long and 20 centimeters in diameter (Fig. 4). Each point on Figure 4 is occupied by an accelerator neutrino source, (Fig. 5). Plasma-based accelerators are already producing high-energy particle beams; what a K2 civilization may be capable of for accelerators is an extrapolation. With 10^{18} accelerators pointing four pi radians, the probability of detection increases to approximately 10^{-3} and the detection rate at 10,000 light years becomes approximately 5 per minute. The power required for the whole artifact’ is about .01 Solar, which is a K2 command of energy.

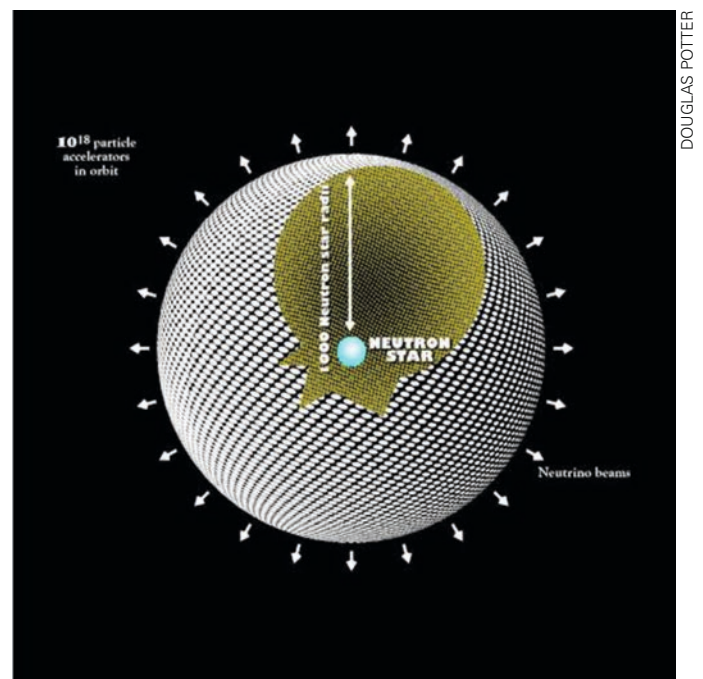


Fig.4 A representational Constellation of 10^{18} accelerator-transmitters in orbit (nothing to scale).

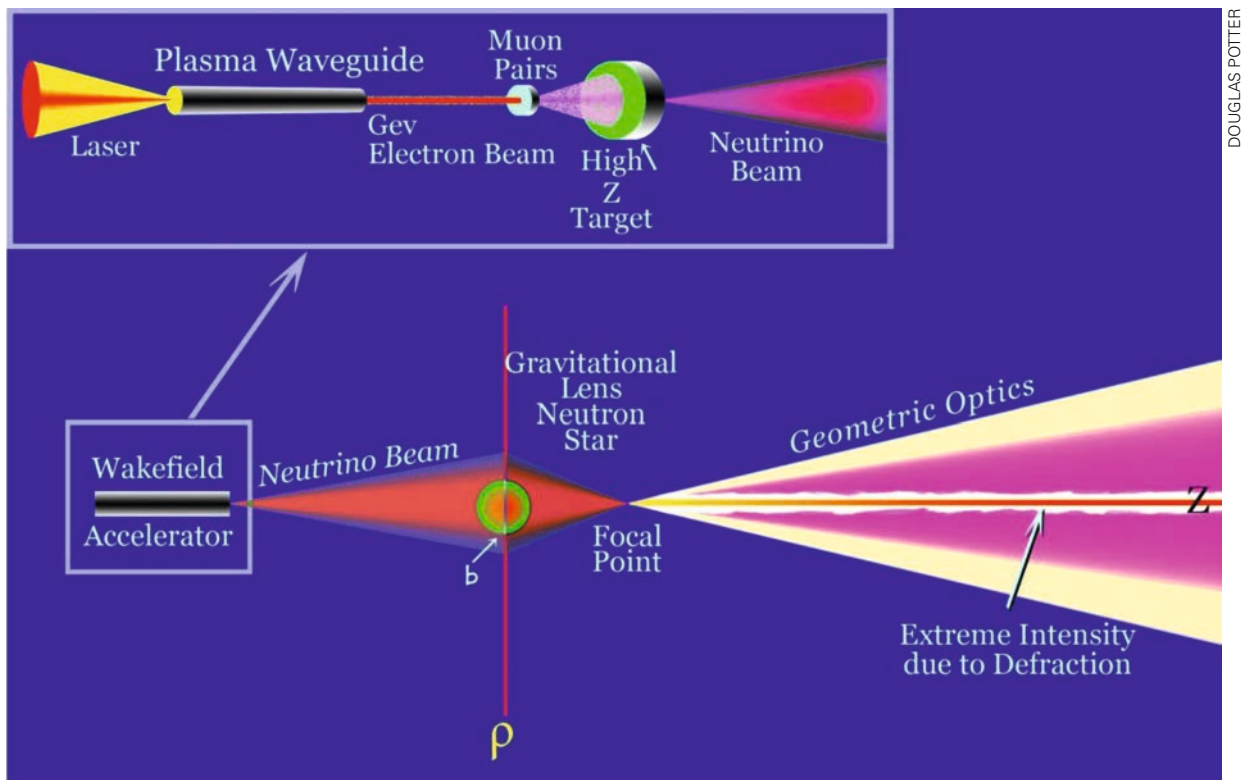


Fig.5 A schematic illustration of a possible neutrino accelerator-transmitter, the accelerator and lens (nothing to scale).

Of note, there is one constraint the advanced civilization must master. The transmitters in the orbital constellation must be configured so as to appear to the gravitational lens as point-sources. It will be supposed that a K2 technology can master this technology.

It is also possible for the gravitational lens to be a black hole, however the results are nearly same except for 'glory' scattering, radiation scattered 'backward', which may be of advantage [23]. Scattering by a rotating black hole is very complicated matter and is not dealt with here.

5.0 CONCLUSIONS

An instrumentality has been presented for directed neutrino signal transmission. The 'beam' could encode information in a neutrino beam by on-off keying, or a more sophisticated modulation is possible [24]. An advanced civilization may deploy

such a beacon as a 'honey-pot' to attract attention to an electromagnetic transmitter broadcasting more information in a sophisticated manner. The 'artifact' presented here is a thought experiment: a Kardashev 2 civilization would likely have the resources to finesse the technology and master system efficiencies in a smarter way.

The remarkable element is that a neutrino source can be fabricated to produce extraordinary number of detection events at cosmic distances. The signal-to-noise ratio at MeV may not even be a problem if the detection rate is high. There may be waste heat from the operation of this technology, even if in the infrared it looks a bit odd.

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APPENDIX A

Engineering physics problems an advanced civilization has to solve:

(1) The point-like nature of the transmitting aperture can be estimated. In the paper by Matsunaga and Yamamoto [25], calculate the Einstein angle:

$$\theta_e = \sqrt{\frac{4GMd_{ls}}{c^2d_s^2}} \quad (A1)$$

M is the mass on the lens, d_{ls} is the distance of the transmitter from the lens and d_l is the distance of the lens from the target, then the size of the transmitting aperture (not the size of the

transmitter) is:

$$s = \frac{d_s \theta_e}{\sqrt{w}} \quad (A2)$$

That is approximately 40 microns for the thought experiment here, the realization of which will require the ingenuity of a K2 civilization.

(2) The modeling in section 2 is highly idealized, the wave optics being calculated on the assumption of plane waves and that the gravitational lens is spherical. For a non-rotating black hole, sphericity is satisfied; however for a neutron star, small departures from a sphere are possible. Accretion of matter,

crust stresses and magnetic fields can cause a deformation. If the departure from a perfect sphere is measured by a small parameter ϵ then it can be shown that the lens magnification gain (8) is reduced by [26]:

$$\text{gain}_{\text{reduced}} \approx \frac{.25}{\sqrt{\epsilon \text{gain}_0}}, \epsilon \text{gain}_0 \gg 1 \quad (\text{A3})$$

A deformation of a neutron star will induce a quadrupole moment, the maximum ϵ can be as large as 10^{-4} , however the in-

duced gravitational radiation will dissipate the distortion from a sphere on the order of seconds.

(3) Orbital configuration. At 1000 neutron star radii the orbital speed is .01c at about .1 radian/sec which will be a guidance, navigation and control problem, only a civilization with interstellar flight could solve. To be noted, at 100 neutron star radii the tidal forces on a solid vehicle of steel will be quite small, for a black hole the constellation would have to be inside 10 Schwarzschild radii to notice departures from Newtonian mechanics.

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