Superluminal transmission of phase modulation information by a large macroscopic pulse propagating through interstellar space

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Abstract

A method of transmitting information in interstellar space at superluminal, or $> c$, speeds is proposed. The information is encoded as phase modulation of an electromagnetic wave of constant intensity, i.e. fluctuations in the rate of energy transport plays no role in the communication, and no energy is transported at speed $> c$. Of course, such a constant wave can ultimately last only the duration of its enveloping wave packet. However, as a unique feature of this paper, we assume the source is sufficiently steady to be capable of emitting wave packets, or pulses, of size much larger than the separation between sender and receiver. Therefore, if a pre-existing and enduring wave envelope already connects the two sides, the subluminal nature of the envelope’s group velocity will no longer slow down the communication, which is now limited by the speed at which information encoded as phase modulation propagates through the plasma, i.e. the phase velocity $v_p > c$. The method involves no sharp structure in either time or frequency. As a working example, we considered two spaceships separated by 1 lt-s in the local hot bubble, to demonstrate that provided the bandwidth of the extra Fourier modes generated by the phase modulation is much smaller than the carrier wave frequency, the radio communication of a very specific message can take place at a speed in excess of light by a few parts in $10^{11}$ at $\nu \approx 1$ GHz, and even higher at smaller $\nu$. 

INTRODUCTION

At the current stage of our understanding of relativity theory, it is universally accepted that material particles cannot move at superluminal (i.e. > c) speeds without invalidating the theory at its core. The situation is less stringent about information, however. If information can be communicated superluminally, special relativity could then be used to construct various paradoxes pertaining to causality, but it is debatable if any of them would lead to irreconcilable contradiction with observational experience, [1]. Obviously, an important exception to the statement, is the scenario of informational transmission by particles, which is still the most commonly pursued means of communication in the world. Nevertheless, there has recently been a wealth of publications on the subject of quantum communication without the transport of particles, an endeavor sometimes referred to as ‘detection without measurement’, see [2] and subsequent citations of this paper. That said, it should still be emphasized that none of the ideas and experiment performed on them were about superluminal information transfer. Thus, e.g. it is well known that the phenomenon of ‘wavefunction collapse’ of quantum entangled states cannot be exploited to facilitate such a transfer, because of the random, unpredictable, and uncontrollable outcome of the collapse, [3].

In this paper a method of transmitting information that does not directly involve particles (which include wave packets and quanta) is proposed in an astrophysical context, by considering two observers in the local bubble of the interstellar medium – sender and receiver – one of whom could be somebody in a spaceship orbiting planet earth. The method utilizes the property of superluminal phase velocity in a dispersive medium. It is, as will be shown below, unrelated to a recent controversy over the superluminal group velocity of a wave packet in a spectral region far below the resonance of an inverted two-level atomic medium ([4], [5]), a scenario that does not ultimately leads to superluminal transport of energy because of the narrow bandwidth occupied by the frequencies for which superluminal group velocity apply,[6]. Specifically, in order for a pulse to unambiguously be determined as propagating at > c speed, it has to have a sufficiently sharp edge, which in turn mandates a wide bandwidth of frequencies. As a result, not only does the Taylor expansion for $k(\omega)$ converges slowly, extending beyond the third term, but also many modes of significant amplitude have frequencies so high that they lie outside the bandwidth of superluminality.
The method proposed here, on the other hand, operates in a region where the refractive index varies smoothly and featurelessly with frequency. It also involves an extremely narrow bandwidth, one that converges after the first two Taylor expansion terms for $k(\omega)$.

**EFFECT OF A DISPERSIVE MEDIUM ON A PHASE MODULATED SIGNAL: SIMPLE MODEL**

Let us remind ourselves of the standard treatment of the effect of dispersive medium on a propagating electromagnetic wave, see e.g. [7], or [8]. If the medium is vacuum, it is usual to express the wave amplitude as that of a monochromatic beam of frequency $\omega_0$ (known as the carrier wave) directed along $+z$ and spanning some finite duration $\approx \sigma$, namely

$$\psi(t, z) = \frac{a}{\sqrt{\sigma}} e^{-\left(\frac{t-z}{2\sigma}\right)^2} e^{-i\omega_0(t-z)}, \quad (1)$$

where $a$ is an arbitrary constant ($a = \pi^{-1/4}$ if the intensity $I = |\psi|^2 = 1$) and $c = 1$. The form given by (1) is sometimes known as a Gaussian wave packet. Suppose we let such a wave packet be emitted with its center at $t = 0$ and $z = 0$, so that its amplitude at the emitter's position and for times immediately on either side of $t = 0$ is

$$\psi_e(t) = \frac{a}{\sqrt{\sigma}} e^{-t^2/(2\sigma^2)} e^{-i\omega_0 t}. \quad (2)$$

Now let the signal propagate a distance $z$ through a uniform dispersive medium to reach some downstream position $z$. The wave amplitude would then be found to vary with time at this position as

$$\psi_0(t, z) = \frac{a}{\sqrt{\sigma}} \exp \left[ - \left( \frac{t - z/v_g}{\sqrt{2} \sigma} \right)^2 \right] e^{-i\omega_0(t - z/v_p)}, \quad (3)$$

where $v_p = \omega_0/k_0$ and $v_g = (d\omega/dk)_{k=k_0}$ are the phase and group velocity of the wave packet in the medium, and in (3) we ignored the spreading of the wave packet due to the $\omega'' = (d^2\omega/dk^2)_{k=k_0}$ effect, which becomes significant only when the propagation length $z$ is large.

For most dispersive media, the group velocity $v_g = \omega'_0 < 1$. Thus the energy of the wave within the Gaussian envelope of the wave packet is transported subluminally, in accordance with special relativity. This is certainly the case of interstellar communication through a
plasma medium, where the two velocities are

\[ v_p = \frac{\omega_0}{k_0} = \left(1 - \frac{\omega_p^2}{\omega_0^2}\right)^{-1/2} \approx 1 + \frac{\omega_p^2}{2\omega_0^2}, \]  

(4)

and

\[ v_g = \left(\frac{d\omega}{dk}\right)_{k=k_0} = \left(1 - \frac{\omega_p^2}{\omega_0^2}\right)^{1/2} \approx 1 - \frac{\omega_p^2}{2\omega_0^2}. \]  

(5)

the last expression for each velocity is valid in the limit \( \omega_0 \gg \omega_p \). Note however that the phase velocity \( v_p > 1 \) and, even though phase is unrelated to energy transport, it could carry useful information a sender wishes to convey to a receiver. The reason why one usually does not consider this point noteworthy is two-fold. First is because most forms of communication relies on energy or particle transport, either of which is invariably limited by the group velocity. Second, phase information can only be detected if the wave has appreciable amplitude, which does not occur unless and until the Gaussian envelope of the wave has reached the receiver’s end. This means the actual arrival time of information is still effectively determined by \( v_g \), and superluminal transmission of information is impossible.

But the situation radically changes if the Gaussian envelope has a width \( \sigma \) far exceeding the distance of separation \( \ell \) between the sender and receiver, corresponding to the scenario of a highly steady (long pulse) emitter, because the receiver can now see the wave at all times; and any information the sender wishes to convey by modulating the wave phase could, at least in principle, be transmitted across at the speed \( v_p > 1 \).

Let us consider the simple model of sinusoidal phase modulation at the period \( 2\pi/\Omega \) where \( \Omega \ll \omega_0 \). Specifically, we assume in (1) a very large \( \sigma \) that enables us to ignore the Gaussian envelope altogether, but allows the wave to have a slowly and sinusoidally varying phase of the form \( \phi(t) = \xi \sin \Omega t \). In even more precise terms, this requires

\[ \sigma \gg \ell \gg \frac{1}{\delta\omega} \gg \frac{1}{\omega_0}, \]  

(6)

where \( \delta\omega \) is the spectral bandwidth of Fourier modes generated by the phase modulation, in which case the undispersed wave is modified from (1) to become

\[ \psi_e(t, z) = ae^{-i\omega_0(t-z)}e^{i\xi \sin \Omega(t-z)} \]  

(7)

where the subscript denotes ‘emission’. Once again as before, we may take \( z = 0 \) as the spacetime position of the sender, \( i.e. \) the amplitude experienced by the sender is

\[ \psi_e(t, z = 0) = \psi_e(t) = ae^{-i\omega_0 t}e^{i\xi \sin \Omega t}. \]  

(8)
Note that under this scenario it is possible, though unnecessary, to assign \( t = 0 \) as the time of signal emission, because without the Gaussian envelope there is neither a preferred position at any given time, nor vice versa. An important point to be made about (7) and (8) is that the intensity \( \psi \psi^* \) of the signal equals a constant (this statement is classical and ignores the shot noise of photons, but in radio frequencies where most communications are held the photon occupation number is large enough for shot noise to be negligible). For all \( t \) and \( z \), i.e. information is being transmitted via the changes in \( \phi \) and not the intensity. Therefore, unlike conventional methods, the communication is not effected by any direct enlistment of systematic transport of energy (or, more precisely, energy changes), which cannot take place at superluminal speeds.

To account for the way this signal is affected by its passage through the dispersive medium of the interstellar plasma, we first define coordinates such that emission takes place at \( t = 0 \) and \( z = 0 \) (which means the receiver is somewhere on the \( z \)-axis, say \( z = \ell \)).

SUPERLUMINAL TRANSMISSION OF PHASE MODULATION INFORMATION IN THE INTERSTELLAR MEDIUM

Since dispersion effects can only be calculated in reliable terms for individual frequency modes, but when the phase of the carrier wave is modulated as in (7) the ensuing signal is a linear superposition of multiple modes (as in the case of the wave being enveloped by a Gaussian), one needs to look at the behavior of each individual Fourier mode of the dispersed signal.

The amplitude of a mode of frequency \( \omega \) that comprised (7) is given by the Fourier transform of \( \psi \), namely

\[
\tilde{\psi}_e(\omega) = \int_{-\infty}^{\infty} \psi_e(t)e^{i\omega t} dt = 2\pi a \sum_{m=-\infty}^{\infty} J_m(\xi)\delta(\omega - \omega_0 + m\Omega), \tag{9}
\]

where \( J_m \) is the Bessel Function of order \( m \), and use was made of the Jacobi identity

\[
e^{ix\sin \theta} = \sum_{m=-\infty}^{\infty} J_m(x)e^{im\theta}. \tag{10}
\]

Thus the spectrum of radiation consists of lines at frequencies

\[
\omega = \omega_m = \omega_0 \pm m\Omega, \text{ for } m = 0, 1, 2, \ldots \tag{11}
\]
In the case of $0 < \xi < 1$ (there is no need to have $\xi > 1$ since we are modulating a phase) one can get a feel for the width of the spectrum under the two limiting scenarios of $\xi \ll 1$ and $\xi \to 1$. For the former, the Bessel functions assume the asymptotic form of

$$J_m(x) = \frac{1}{m!} \left( \frac{x}{2} \right)^m, \quad x \ll 1 \text{ and } m = 0, 1, 2, \cdots$$

(12)

and hence the spectral width is $\approx \Omega$ (note that negative values of $m$ also give the same width because of the exact relation $J_{-m}(x) = (-1)^m J_m(x)$ which holds for all $x$ and integral values of $m$). For the latter, $J_m(x)$ is peaked at harmonic number $m \approx (1 - x^2)^{-3/2}$ and cuts off exponentially after that, hence the width is $\approx (1 - \xi^2)^{-3/2}\Omega \gg \Omega$. In summary

$$\delta \omega \approx \Omega, \text{ for } \xi \ll 1; \text{ and } (1 - \xi^2)^{-3/2}\Omega \text{ for } \xi \to 1.$$  

(13)

When dispersion is taken into account, the amplitude of the mode of frequency given by (11) becomes, at the receiver’s coordinates $(t, z)$,

$$\psi_m(t, z) = 2\pi a J_m(\xi) e^{-i\omega_m t + i\omega_0 z/v_p + i(\omega_m - \omega_0) z/v_p + ik''_0(\omega_m - \omega_0)^2 z/2 + \cdots},$$

(14)

where $\omega_m$ is given by (11) and $k''_0 = (d^2 k/d\omega^2)_{\omega_0}$. The total amplitude $\psi_r(t, z)$ at the receiver is

$$\psi_r(t, z) = \sum_m \psi_m(t, z).$$

(15)

As in the case of a wave packet, the $k''_0$ term (and higher order terms) in the exponent may be ignored if it is $\ll 1$ or, equivalently, if the bandwidth of (13) and the distance propagated $z = \ell$ satisfies the criterion

$$\frac{1}{2} k''_0(\omega - \omega_0)^2 z = 2.65 \times 10^{-8} \left( \frac{n_e}{0.1 \text{ cm}^{-3}} \right) \left( \frac{\omega_0}{6 \text{ GHz}} \right)^{-1} \left( \frac{\delta \omega/\omega_0}{10^{-3}} \right)^2 \left( \frac{z}{1 \text{ lt s}} \right) \ll 1$$

(16)

The inequality of (16) allows us to write, with the aid of (14), the phase of the mode as

$$\varphi_m(t, z) = -\omega_m \left[ t - \frac{\omega_0 z}{\omega_m v_p} - \frac{(\omega_m - \omega_0) z}{\omega_m v_g} \right].$$

(17)

where $v_p$ and $v_g$ are respectively the phase and group velocities of the $\omega_m = \omega_0$ (or $m = 0$) mode, see (4) and (5). The phase velocity of any mode of frequency $\omega_m$ as in (11) is then obtained by solving for $\dot{z}$ under the condition $\varphi_m = \text{constant}$, or $d\varphi_m/dt = 0$, which yields

$$\left( \frac{\omega_0}{\omega_m v_p} + \frac{\omega_m - \omega_0}{\omega_m v_g} \right) \dot{z} = 1 \implies \dot{z} \approx v_p,$$

(18)
where the next order of small quantities correction to the \( \approx \) sign is of order \( \omega_p^2 \delta \omega / \omega_0^2 \) if (as is most likely the case) \( \omega_p^2 / \omega_0^2 \ll \delta \omega / \omega_0 \), and of order \( \omega_p^4 / \omega_0^4 \) otherwise. There are no terms of order \( (\delta \omega / \omega_0)^n \) with \( n > 1 \).

Thus, provided the criteria

\[
\frac{\omega_p^2}{\omega_0^2} \ll \frac{\delta \omega}{\omega_0} \ll 1, \quad \text{and} \quad \frac{\omega_p^2 z \delta \omega}{\omega_0^2 v_p} \ll 1
\]

are also satisfied (i.e. in addition to the inequalities (6) and (16)), a mode of any frequency \( \omega \) as given by (11) will propagate so close to the phase velocity \( v_p \) of the central frequency mode \( \omega = \omega_0 \), namely (4), that it leaves behind no significant phase error by the end of the journey – the last inequality enforces this. Since \( v_p > 1 \), it is then clear that the information encoded in the phase modulation is distributed among all the modes, which carry it to other parts of space at the same superluminal speed \( v_p \). The signal is then transmitted to the receiver at the speed \( v_p \) without distortion.

We now have the proof that under the criteria of (6), (16), and (19), phase encoded messages can indeed be superluminally communicated from sender to receiver. In fact, the same claim can be made about a carrier wave enveloped by a short pulse, (1), because a wave front of the carrier wave will, under the same three criteria, propagate at speed \( v_p > 1 \) and arrive at the receiver slightly ahead of the vacuum light travel time, but has not yet moved outside the envelope (which lags behind as a result of its \( v_g < 1 \) speed). Thus the wave front still has an appreciable amplitude. Of course, to transmit meaningful information one needs to modulate the phase of the wave front, which is not done in (1).

It should also be apparent that although in (7) we chose to work on the specific example of a sinusoidally modulated phase, the same conclusion may be made about any information being communicated by a more complex signal of real life, provided the bandwidth \( \delta \omega \) and other relevant parameters satisfy the same aforementioned criteria. To be very clear, consider a general phase modulation function \( \varphi(t) \), which could e.g. be a Gaussian, such that the second exponent of (8) is now \( i \varphi(t) \); and let \( \tilde{\psi}_e(\omega) \) be the Fourier transform of \( \psi_e(t) \) where the latter is as defined in (9a).

Provided \( n_e, z, \omega_p, \omega_0 \), and the range of extra frequencies that arose as a result of the phase modulation (namely the width \( \delta \omega \) of \( \tilde{\psi}_e(\omega) \), e.g. if \( \varphi(t) \) is a Gaussian of duration \( \delta t \gg 1/\omega_0 \) and height \( \xi < 1 \) then \( \delta \omega \approx 1/\delta t \) will obey the three criteria (6), (16), and (19),
so one can write (14) and (15) in context as

\[ \psi_r(t, z) = \int \tilde{\psi}_e(\omega) e^{-i\omega t + i\omega_0 z/v_p + i(\omega - \omega_0)z/v_g} d\omega = a e^{-i\omega_0(t - z/v_p) + i\varphi(t - z/v_g)} \]  

(20)

where \( \varphi \) in the second exponent does not multiply the quantity \( t - z/v_g \) but is a function of it. Note again that the third and higher order terms in (14) are negligible and ignored because of the three criteria. The phase velocity of a signal wavefront is then obtained by differentiating the total exponent in the final output of (20) w.r.t. \( t \) and equating it to zero, which yields

\[ \dot{z} = \frac{(1 - \dot{\varphi}/\omega_0)(1 + \epsilon)}{[1 - \dot{\varphi}(1 + \epsilon)^2/\omega_0]}, \]  

(21)

where we wrote (4) and (5) as \( v_p = 1 + \epsilon \) and \( v_g = 1/v_p \) with \( \epsilon \ll 1 \). Again, provided (19b) holds, \( |\dot{\varphi}|_{\text{max}} \approx \delta \omega \ll \omega_0 \), and so (21) reduces to \( \dot{z} = v_p \) to lowest order. Moreover, the time dependence of \( \dot{z} \) here is all in the higher order terms, so that the wavefronts propagate at the same constant speed \( v_p > 1 \) to within very small differences.

The signal will then be transmitted superluminally; it will remain minimally distorted after it was sent, if the total distance propagated \( z = \ell \) is not large enough for these tiny speed differentials to perturb the separation between wavefronts by amounts as large as \( v_p/\delta \omega \). This condition is the same as (19c). To elaborate, although there is a slight distortion due to the difference between \( v_p \) and \( v_g \) in (20), it will be wrong to conclude that the second exponential means any information encoded as phase anomaly is transmitted at the group velocity. In fact, as will be discussed in the next section, one can encode messages in such a way as to exploit the alignment between the carrier wave phase and the anomalous phase, so that the superluminal velocity of the former can more than compensate for the subluminal velocity of the latter.

Thus, unlike e.g. [4] and [5], the bandwidth here is extremely narrow, and the Taylor expansion for \( k(\omega) \) does not extend beyond the first two terms. Any high frequency components lying outside the requisite bandwidth that fulfills (6), (16), and (19) are likewise absent from in this form of communication, which can then take place superluminally without any inherent difficulty. Another important difference between current and previous approach is that while superluminal group velocity exists within a very narrow frequency band centered at the resonance frequency of the medium, superluminal phase velocity in a plasma occurs in an extremely broad band within which the refractive index \( n(\omega) \) is smooth and featureless. The only requirement is \( \omega > \omega_p \). In the example we provided, the plasma frequency of the
local interstellar medium is $\approx 2 \times 10^4$ Hz, while the carrier wave frequency is 300,000 time higher, at $\approx 6$ GHz. There is in fact no way the phase modulation process could possibly induce subluminal Fourier components with frequencies lying below the plasma frequency.

TECHNOLOGICAL CONSIDERATIONS; SUPERLUMINAL TRANSMISSION OF A SPECIFIC MESSAGE

How might an actual communication channel look like? To demonstrate that one is already on the threshold of technological feasibility, we restrict our consideration to two spaceships $\approx 1$ lt s apart (i.e. $\ell \approx 3 \times 10^{10}$ cm) in the local bubble of the interstellar medium, where the principal plasma component is a $\approx 7,000$ K partially ionized gas with a free electron density $n_e \approx 0.1$ cm$^{-3}$, [9]. The beam linking the two spaceships could be coherent radio waves at $\omega_0 = 6$ GHz ($\nu_0 \approx 1$ GHz). The duration of the wave packet envelope is assumed to be $\sigma \approx 100$ s. State-of-the-art microwave generators, especially those based on optical resonators, can readily achieve a fractional frequency instability in the $10^{-16}$ range at 10 GHz, [10], making this technological requirement easily achievable. In fact, such a fractional error would mean that at 1 GHz the wave packet can be as large as 1/3 lt-yr.

Information coding can be accomplished by passing the carrier wave through a phase modulator with a bandwidth much smaller than the carrier, e.g., $\delta \omega \approx 1$ MHz. Phase modulation has become a mature technology over the last three decades due to the advance in microwave and optical communications, [11], [12].

In this way the reader can readily verify that the criteria (6), (16), and (19), are all met. Moreover, the phase error among modes resulting from the small departure of $v_p$ from constancy (w.r.t. modes, see the discussion around (18) and (19)) leads only to $= \ell \omega_p^2 \delta \omega / (v_p \omega_0^2) \approx 3 \times 10^{-5}$ radians inaccuracy in the phase of a mode’s wavefront. The encoded message will then be sent from one spaceship to the other at the phase velocity $v_p$, which, by (4), exceeds $c$ by $\approx 2$ parts in $10^{11}$. Such a speed excess causes a systematic phase advance $\approx 0.03$ radian (w.r.t. the $v_p = 1 = c$ scenario), or $1.6^\circ$ for all relevant modes. In order to test its existence, the receiver has to be able to measure the phase of the arriving wave fronts with sufficient accuracy. This requires a stable oscillator, i.e. a clock, synchronized to the oscillator of the sender. Currently available optical atomic clocks can routinely reach fractional frequency instabilities at the $10^{-17}$ level, [13], and remote
(920 km) frequency metrology as accurate as a few parts in $10^{18}$ has been demonstrated, [14]. Although metrology across a 1 lt s channel has not been realized experimentally, no fundamental inhibition is known. Once the clocks at the two ends are cross-calibrated, phase advances as small as a fraction of one degree would stand well above clock noises, i.e. their presence by such an amount (which is readily detectable with the heterodyne technique, [15]) would then represent a real effect.

As a concrete example, suppose information in the form of the binary digit 0 is encoded as the alignment of the zero phase of the carrier wave with the peak of a Gaussian modulation waveform $\varphi(t)$ for the anomalous phase (the binary digit 1 may then be encoded by aligning carrier phase $\pi$ with the Gaussian peak). Specifically the sender’s signal is as in (8) with the second exponent replaced by $i \xi \exp[-t^2/(\sqrt{2} \delta t)^2]$, where $\xi = 0.5$ and $\delta t \approx 1/\delta \omega$ and all other parameters are on par with values quoted in the first two paragraphs of this section. The transmitted amplitude will then be given by (20) with $i \xi \exp[-(t - z/v_p)^2/(\sqrt{2} \delta t)^2]$ as the 2nd exponent. Since the wavefront of interest is the one that left the sender at $t = 0$ with the phase $\phi = \xi$, one can easily verify that the arrival time of this wavefront at the receiver is extremely close to $t = z/v_p$, because the phase at this time is entirely due to the anomalous component, and is equal to $\xi$ to within an error of one part in $10^9$ (the second iteration solution is $t = z/v_p + z^2 \omega_0^4 \xi (\delta \omega)^2/(2 \omega_0^5 v_p^2) \approx z/v_p$, which aligns the phase with $\xi$ to one part in $10^{17}$). On the other hand, if one were to let $t = z/c$ or $t = z/v_g$ to be the arrival time, the systematic error in the phase would be of order the 1.6$^\circ$ (or 0.03 rad) quoted in the previous paragraph, which is offset from $\phi = \xi$ by as large as 6%. Next, when comparing against $t = z/v_p \pm 2\pi/\omega_0$, the phase for both of them differ from $\phi = \xi$ by about 1 part in $10^6$, i.e. the offset is still 1,000 times larger than the correct arrival time of the message, $t \approx z/v_p$. Note that the receiver can check the carrier phase at anytime, if the sender transmits additionally the unmodulated carrier wave via a beam splitter.

It is also possible to envisage the sender encoding the binary 0 digit by aligning at $t = 0$ the carrier wave’s phase zero with the mid-point $\xi/2$ of the rising Gaussian wing of the anomalous phase. Under such a scenario, the $t = z/v_p$ solution yields an entirely anomalous phase, which differs from $\xi/2$ by about 3 parts in $10^4$. At $t = z/c$ and $t = z/v_g$, however, the discrepancy becomes 10% (0.03 rad), while at $t = z/v_p \pm 2\pi/\omega_0$ it is 2.5% (0.006 rad). Thus, as before, all the wrong solutions yield much more phase misalignments which, in this instance, are large enough to be readily detectable as well.
Some drawbacks in our proposed scheme are the smallness of the distance between the two observers, which cannot be so large that a wavefront overtakes luminal propagation by an amount greater than the duration of the phase modulation (or else any message encoded as degree of alignment between the normal and anomalous phases will be distorted beyond recognition), and the issue of communication interruption when the long pulse (i.e. large $\sigma$) emitted by the source runs out. It should nevertheless be emphasized that, in spite of the shortcomings, this is the first endeavor to establish a stable communication link over some meaningful separation in interstellar space, that demonstrated as matter of principle the prospect of superluminal transmission of information. The difficulties remaining are indeed formidable, but there does not appear to be any fundamental reasons why they cannot be overcome.

CONCLUSION

In conclusion, a ‘proof of principle’ demonstration of superluminal communication in the interstellar medium is provided, based on currently available or imminently accessible technologies. It utilizes a large pre-existing wave packet of size far exceeding the sender-receiver separation. By means of this very steady beam, phase modulation information is then transmitted through the dispersive medium of the interstellar plasma, at the phase velocity of $v_p > c$. The physical implications of superluminal information has extensively been addressed in the literature (see e.g. [1]) and will not be discussed here, safe to say that the consequences are generally not as catastrophically envisioned as superluminal energy transport.

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