# Write or Radiate?

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***Abstract*— We consider information flow via physical transport of inscribed media through space and compare it to information flow via electromagnetic radiation. Somewhat counterintuitively for point to point links, physical transport of inscribed mass is often energetically more efficient by many orders of magnitude than electromagnetic broadcast. And perhaps more surprising, even in a broadcast setting (depending on the receiver density) inscribed mass transport is still energetically more efficient. We examine these results for terrestrial telecommunications as well as point to point and broadcast communication over great distances with loose delay constraints.**

## I. Introduction

At one time or another, every communications theorist has had the following epiphany:

> *Driving a truck filled with storage media (books, cd's, tapes, etc.) across town constitutes a very reliable channel with an extremely large bit rate.*

For example, Rolf Landauer mentioned the possibility of inscription and physical transport [1] in the context of reversible communication. Similarly, Gray *et al* [2] considers the viability of information carriage through transport of mass storage media from an economic perspective.

My own epiphany has occurred a few times over many years, but most recently with the study of short range high data rate channels [3]–[5] and mobility-assisted wireless networks [6], [7] where communications nodes only transfer data to one another when the channel is good – typically at close range. One natural extension of this work is to not radiate electromagnetic energy at all, but rather, to have nodes physically exchange "letters" inscribed on some medium. And from such imaginings comes a simple question: when is it better to write than to radiate?

To begin, consider that one could easily pack ten 60 GByte laptop disk packs in a small box and push it across a table – with a correspondingly impressive data rate of about 4.8 Tb/second. Without much imagination, the idea can be extended to more exotic storage media. Consider a 1 $\text{mm}^3$ "bouillon cube" containing information coded as single stranded RNA (such as the polio virus). At about 1 base per $\text{nm}^3$ [8], [9], each cube could store about 1000 Petabits ($10^{18}$ bits) of information. A $10\text{cm}^3$ volume of such material, if driven from New York to Boston in an automobile would constitute a rate of about $90,000$ Petabits/second ($9\times10^{19}$bps) – dwarfing by about six orders of magnitude the 100 Terabit per second theoretical maximum information rate over optical fiber [10].

Next consider the mass of 1000 Petabits since mass will determine the amount of energy necessary for transport. Again using the virus analogy, single stranded RNA has an average mass of about 330 kDa per kilobase. A Dalton (Da) is the molecular weight of hydrogen and is about $1.67\times10^{-24}$g [11]. So, the $10^{15}$ kilobases implied by 1000 Petabits would weigh $330,000\times10^{15}$ Da. Conversion to more familiar units shows the total mass of our hypothetical 1000 Petabit message would be $551\mu$g. The *mass information density* would be

$$\rho = 1.82\times10^{24}\text{bits/kg} \tag{1}$$

which we will later see is about two orders of magnitude better than rough extrapolations based on the current best micropatterning technology [12].

This impressive figure, however, may leave *some* room at the bottom. That is, there is no published theoretical limit to the amount of information that can be reliably stored as ordered mass. Thus, although Feynman argued a conservative bound of $5\times5\times5$ atoms per bit [13], [14], and RNA molecules achieve densities on the order of $32$ atoms per bit [15], our $\approx$ 2000 Petabit/gram biological "existence proof" could be overly pessimistic by one or more orders of magnitude. Regardless, the point is that it is not hard to imagine large amounts of information being stored reliably and compactly using very little mass.

So, why hasn't inscribed mass transport been exploited in modern telecommunications networks? There are a number of reasons, but two seemingly obvious answers spring to mind. First, the key problem in telecommunications is *energy efficient* transport of information and delivering inscribed mass from New York to Boston would seem to consume a great deal of energy. Second, modern networks require *rapid* transport of information while the NY-Boston trip requires approximately 3 hours by car – or a few hundred seconds ballistically. These "answers" illustrate the key tensions which concern all telecommunications theorists:

*tolerable delay* vs. *tolerable energy* vs. *tolerable throughput*

In quantifying these tensions for what we will call *inscribed mass channels*, we will find that under a surprising variety of circumstances they are, bit for bit, much more energy efficient than methods based on electromagnetic radiation. Moreover, from a theoretical perspective, the cost of writing the information into some medium can be made infinitessimally small [1], [16], [17], so the energy savings are not necessarily diminished by adding the inscription or readout costs. Thus, something seemingly so primitive as hurling carved pebbles through space can require many orders of magnitude less energy and support dramatically more users than isotropically broadcasting the same information.

And perhaps even more surprising, it is exactly that image which leads to another interesting point. In the regime of very large distances with very loose delay requirements, we will find that mass transport can be many more orders of magnitude more efficient than isotropic radiation. So much so that even if directed radiation methods are used, somewhat heroic engineering, such as very long-lived earth-sized directive apertures, is required to make radiation more efficient than inscribed mass. That is, inscribed mass channels might be a *preferred* way to carry information between specks of matter separated by the vastness of interstellar or intergalactic space.

Though such a conclusion may seem directly at odds with previous work by Cocconi and Morrison [18] which proposed millimeter wave interstellar communications, it is exactly the assumption of loose delay constraints which tips the balance strongly in favor of inscribed mass transport. So, perhaps in addition to scouring the heavens for radio communications from other worlds, we might also wish to more closely examine the seeming detritus which is passing, falling, or has already fallen to earth.

## II. Preliminaries

### A. Definitions and Problem Statement

- $\rho$: mass information density for inscribed information in bits per kilogram.
- $W$: bandwidth available for radiated communication in Hertz.
- $R$: effective receiver aperture radius in meters.
- $A = \pi R^2$: effective receiver aperture in square meters.
- $D$: distance to target in meters.
- $c$: speed of light in meters per second.
- $N_0$: background noise energy in Watts per Hertz (Joules).
- $B$: message size in bits.
- $T$: time allowed, in excess of light-speed propagation delay, for the message to arrive.

We compare the energy required to transport $B$ bits over distance $D$ under delay constraint $T$ using electromagnetic radiation with bandwidth $W$, receiver aperture area $A$ and receiver noise $N_0$ to that required using inscribed mass with information density $\rho$

### B. Empirical Values for Mass Information Density

Detailed consideration of the practicalities of rendering information as inscribed mass and hardening it for transport is provided in separate work [19]. However, it is still useful to examine a few different possible methods of storage to get an empirical feel for "practical" values of mass information density, $\rho$, based on current technology.

At present, RNA base pair storage seems to be the most compact method for which we have an existence proof with a mass information density as stated in the introduction of $\rho_{RNA} = 1.8 \times 10^{24}$bits/kg In comparison, as of this writing a scanning tunneling microscope (STM) can place an equivalent of about $10^{15}$ bits per square inch using individual Xenon atoms on a nickel substrate [12]. The per bit dimension is then $8\text{Å}$ on a side. By somewhat arbitrarily assuming a $100\text{Å}$ nickel buffer between layers we obtain a bit density of $1.55 \times 10^{20}$ bits per cm$^3$. The density of nickel (8.9g per cm$^3$) will predominate owing to the relatively thick layering so that we have

$$\rho_{\text{stm}} = 1.74 \times 10^{19}\text{bits/g} = 1.74 \times 10^{22}\text{bits/kg} \qquad (2)$$

Similarly rough calculations for E-beam lithography, optical lithography and magnetic storage yields

$$\rho_e = (4 \times 10^{18}\text{bits/cm}^3)/(2.6\text{g/cm}^3) = 1.54 \times 10^{21}\text{bits/kg} \qquad (3)$$

$$\rho_{\text{lith}} = (10000Tb/\text{cm}^3)/(2.6g/\text{cm}^3) = 3.85 \times 10^{18}\text{bits/kg} \qquad (4)$$

and

$$\rho_{\text{mag}} = (1000Tb/\text{cm}^3)/(5g/\text{cm}^3) = 2 \times 10^{17}\text{bits/kg} \qquad (5)$$

respectively. Of course, clear limits on the maximum possible density of storage using inscribed mass are unknown. Rough bounds using simple quantum mechanical arguments are provided in [19].

## III. Getting From Here to There

Here we derive lower bounds on the amount of energy necessary to drive a mass $m$ from point $A$ to point $B$ under some deadline $\tau$. We first assume a *free* particle, untroubled by external forces from potential fields (i.e., gravity). We then consider particle motion through potential fields and derive similar energy bounds using variational calculus. Though the results are well known in other fields, for continuity we rederive them here. Also, in keeping with a communication theory flavor, we use only standard communications methods such as basic probability theory and Jensen's inequality.

### A. Jensen's Inequality

Let $h()$ be a non-negative real-valued function of a single variable and let $V$ be a bounded real random variable with mean $E[V] = \bar{v}$. We also assume that $E[h(V)]$ exists. We first note that

$$\max_v h(v) \geq E[h(V)] \qquad (6)$$

and that when $V$ is deterministic

$$\max_v h(v) = E[h(V)] \qquad (7)$$

Next we note that for $h()$ convex we have via Jensen's inequality [20], [21]

$$E[h(V)] \geq h(\bar{v}) \qquad (8)$$

We now use these relations to derive lower bounds on the amount of energy necessary to move particles under delay constraints.

## B. Free Particles

We wish to move a mass $m$ over a distance $D$ within time $\tau$ where the only external force acting on the particle is what we apply. We will assume an inertial frame for source and destination, an initial mass velocity of zero and that we need not bring the mass to rest at the destination. That is, the mass is “caught” by the destination and the only problem is for the source to deliver it on time with minimum applied energy.

Let the particle position be $x(t)$ and its velocity $v(t) = \frac{dx(t)}{dt} = \dot{x}$. Let the intrinsic energy of the particle at velocity $v$ be described by a nondecreasing convex function $h(v)$. In order for the particle to be delivered by time $\tau$ when moved through distance $D$, the average velocity must be $D/\tau$. Specifically,

$$E[v(t)] = \frac{1}{\tau}\int_0^\tau v(t)dt = \bar{v} = \frac{D}{\tau} \tag{9}$$

Equation (9) is equivalent to an expectation of $v(t)$ over a random variable $t$, uniform on $(0, \tau)$.

We seek to minimize the maximum total energy imparted to the particle under the arrival delay constraint. So we seek a trajectory $v(t)$ such that

$$E^* = \min_{v()} \max_t h(v(t)) \tag{10}$$

while requiring $E[v(t)] = \frac{D}{\tau}$. We then note that

$$\min_{v()} \max_t h(v(t)) \geq \min_{v()} E[h(v(t))] \tag{11}$$

and that by Jensen’s inequality

$$E[h(v(t))] \geq h(\bar{v}) \tag{12}$$

with equality iff $v(t)$ is constant. Since $h()$ and $\bar{v}$ are given, $E[h(v(t))]$ has a lower bound independent of the specific trajectory $v(t)$. Therefore we can absolutely minimize $E[h(v(t))]$ by requiring that the particle move at constant velocity. However, this choice of $v(t)$ also causes equation (11) to be satisfied with equality. This leads to the well known result that minimum energy is expended when the particle is launched from its origin with constant velocity $v(t) = D/\tau$, $t \in (0, \tau]$.

For particles approaching light speed we have $h_{\text{total}}(v) = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}}$. However, this total energy includes the rest mass energy $mc^2$. The excess energy owing to velocity is

$$h(v) = mc^2\left(\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} - 1\right) \tag{13}$$

and is convex in $v$, so that the minimum applied energy is

$$E^* = mc^2\left(\frac{1}{\sqrt{1-\left(\frac{\bar{v}}{c}\right)^2}} - 1\right) \tag{14}$$

For particles traveling much slower than light speed ($\bar{v} \ll c$) we have $h(v) \approx \frac{1}{2}mv^2$ so that

$$E^* \approx \frac{1}{2}m\bar{v}^2 \tag{15}$$

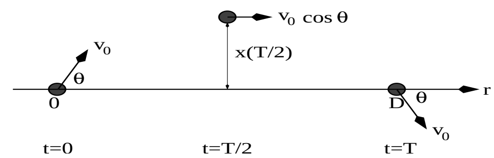


Fig. 1. **The Artillery Problem:** a particle is fired from $x = 0$ at $t = 0$ with initial velocity $v_0$ and angle $\theta$ to land at position $x = D$ at time $t = \tau$.

## C. Particles in a Potential Field

Here we introduce a field which applies force to the particle as a function of position under Newtonian conditions. We will assume conservative (potential) fields such as gravity so that the total energy of the particle is given by

$$\mathcal{E}(t) = h(v(t)) + q(x(t)) \tag{16}$$

where $q(x)$ is the potential energy of the particle at position $x$. We seek the min max energy $\mathcal{E}(t)$ profile which satisfies the particle arrival deadline.

As before, we form an optimization and bound it from below

$$E^* = \min_{x()} \max_t \mathcal{E}(t) \geq \min_{x()} \frac{1}{\tau}\int_0^\tau \mathcal{E}(t)dt \tag{17}$$

We will then minimize the rightmost expression in equation (17) using the calculus of variations [22]. Euler’s equation is

$$\frac{d}{dt}\left(\frac{\partial \mathcal{E}}{\partial v}\right) - \frac{\partial \mathcal{E}}{\partial x} = 0 \tag{18}$$

and application of the definition of $\mathcal{E}(t)$ yields

$$\ddot{x}h''(\dot{x}) - q'(x) = 0 \tag{19}$$

where $\dot{x} = dx/dt = v$ and $\ddot{x} = \dot{v}$.

For low speed motion, $h(v) = mv^2/2$ so that equation (19) becomes

$$m\ddot{x} = q'(x) \tag{20}$$

which implies “free fall” in a potential field since $q'(x)$ is the force on the particle at position $x$. In turn, free fall implies constant energy over the particle trajectory which leads to equation (17) being satisfied with equality. Thus, the particle should be imparted with enough initial velocity $v_0$ such that it reaches the destination at time $\tau$.

The value of $v_0$ depends upon the form of the potential field. For a uniform field where constant force $-\mathbf{F}$ is applied in an inertial frame we have

$$\ddot{\mathbf{x}} = \frac{-\mathbf{F}}{m} \tag{21}$$

If $\mathbf{F} = m\mathbf{g}$, then we have a standard (frictionless) artillery problem as depicted in FIGURE 1. Straightforward calculation yields

$$E = \frac{1}{2}mgD\frac{1}{Dg}\left[\bar{v}^2 + \left(\frac{gD}{2\bar{v}}\right)^2\right] \tag{22}$$

The problem of potential well escape is considered in the journal-length version of this paper [23].

## IV. ENERGY BOUNDS ON INFORMATION DELIVERY

### A. Inscribed Mass

Assuming nothing can exceed the speed of light, we define the message receipt deadline, $T$, as the time allowed *in excess* of the propagation delay with time referenced to the common frames of our two fixed points between which information is sent. The total delay allowed for mass transport is therefore $\tau = (\frac{D}{c} + T)$.

Assuming some value for mass information density $\rho$, the number of bits transported is $B = m\rho$. The energy necessary to transport mass $m$ with deadline $\tau = \frac{D}{c} + T$ in free space with $\bar{v} \ll c$ is then via equation (14)

$$E_w \approx \frac{1}{2}\frac{B}{\rho}\bar{v}^2 \quad (23)$$

For the artillery problem we have via equation (22)

$$E_w = \frac{1}{2}\frac{B}{\rho}\left(\bar{v}^2 + \left(\frac{gD}{2\bar{v}}\right)^2\right) \quad (24)$$

### B. Electromagnetic Transmission

If a transmitter radiates power $P$, a receiver at some distance $D$ will capture some fraction of the radiated power $P_r = \nu(D)P$ where $\nu(D)$ is defined as the energy capture coefficient of the receiver. Assuming square law isotropic propagation loss[1] we have

$$\nu(D) = \frac{A}{4\pi D^2} \quad (25)$$

where $A$ is the effective aperture of the receiver. Assuming additive Gaussian receiver noise, the Shannon capacity [21] in bits per second between the transmitter and receiver is

$$C = W \log_2\left(\frac{PA}{4\pi D^2 N_0 W} + 1\right) \quad (26)$$

where $N_0$ is the background noise spectral intensity and $W$ is the bandwidth of the transmission. If we assume a transmission interval long enough that the usual information theoretic results for long codes can be applied, the number of bits delivered for a transmission of duration $T$ is

$$B = TC = TW \log_2\left(\frac{PA}{4\pi D^2 N_0 W} + 1\right) \quad (27)$$

We note that the time required for arrival of the complete message is $T + \frac{D}{c}$ – identical to the inscribed mass deadline as illustrated in FIGURE 2.

Since $E_r = PT$ we then have

$$E_r = TWN_0\frac{4\pi D^2}{A}\left(2^{\frac{B}{TW}} - 1\right) \quad (28)$$

Long codes imply many channel uses. That is, each bit is coded over multiple "channel uses" where the total number of channel uses is $2TW$ [21]. Thus, we might expect $TW \gg B$. But even if not we can provide a lower bound for equation (28)

[1]For higher loss exponents such as those seen in terrestrial systems, we can multiply the result by the appropriate power of $D$.

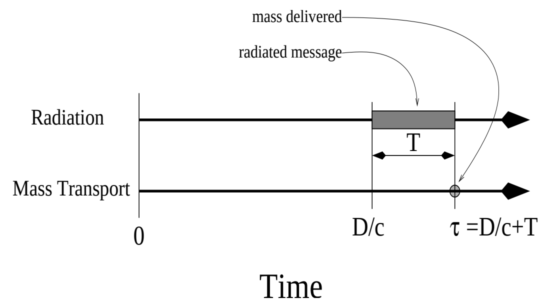


Fig. 2. Temporal comparison of message delivery using radiation and mass transport. $D$: range to target, $c$: speed of light, $T$: radiated message duration, $\tau$: message delivery deadline.

based on such an asymptotic assumption. First we rewrite equation (28) as

$$E_r = BN_0\frac{4\pi D^2}{A}\frac{TW}{B}\left(2^{\frac{B}{TW}} - 1\right) \quad (29)$$

and then since

$$\frac{TW}{B}\left(2^{\frac{B}{TW}} - 1\right) \geq \lim_{\frac{TW}{B}\to\infty}\frac{TW}{B}\left(2^{\frac{B}{TW}} - 1\right) = \ln 2 \quad (30)$$

we must have

$$E_r \geq BN_0\frac{4\pi D^2}{A}\ln 2 \quad (31)$$

It is important to note that although $W$ is often interpreted simply as bandwidth, it is actually a much more general parameter which can be defined to include any number of degrees of freedom one might like – such as polarization, spatial diversity [24] and any others [21], [25], [26]. Thus, in deriving a lower bound on radiated energy based on $\frac{TW}{B} >> 1$ we have essentially allowed infinite (or very large) degrees of freedom by invoking the well known limit

$$\lim_{W\to\infty} W\log\left(\frac{P}{N_0 W} + 1\right) = \frac{P}{N_0} \quad (32)$$

That is, the minimum radiated energy issue boils down to two parameters: 1) how much radiated power is delivered to the receiver, and 2) the receiver noise temperature.

### C. The Radiation to Transport Energy Ratio

We define $\Omega$, the *radiation to transport energy ratio*, as

$$\Omega = \frac{E_r}{E_w} \quad (33)$$

and since $A = \pi R^2$ where $R$ is the receiver aperture radius, we find that for free particle motion at non-relativistic speeds we have

$$\Omega_f \geq (8\ln 2)\frac{\rho N_0}{\bar{v}^2}\left(\frac{D}{R}\right)^2 \quad (34)$$

For the artillery problem we have

$$\Omega_a \geq \rho N_0(8\ln 2)\left(\frac{D}{R}\right)^2\frac{1}{\bar{v}^2 + \left(\frac{gD}{2\bar{v}}\right)^2} \quad (35)$$

## V. Results for Point-to-Point Links

### A. Isotropic Radiation

Here we plot the energy ratio $\Omega$ for point to point links first assuming free space isotropic propagation over large distances (interstellar) and then terrestrial conditions. For terrestrial systems we assume a temperature of $300°$K and a receiver aperture on the order of $R = 0.1$m at ranges up to 10 kilometers. For interstellar conditions we use a receiver temperature of $3°$K and receiver apertures of $150m$ (Arecibo radio telescope) and $R = 6.38 \times 10^6$km (earth radius) at one lightyear and above.

In all cases, inscribed mass channels are many orders of magnitude more efficient than isotropic radiative channels. For example, using earth-sized apertures, we see in FIGURE 3 that for a mean speed of $\bar{v} = 10^{-3}c$, inscribed mass requires $10^{10}$ less energy than electromagnetic radiation at a range of one lightyear. At ten thousand lightyears, this gain is $10^{18}$. For an Arecibo-sized aperture, the energy gain of mass over radiation is a factor of about $10^{19}$ at one lightyear and $10^{27}$ at ten thousand lightyears as may also be seen in FIGURE 3. These gains are, for lack of a better word, astronomical.

For terrestrial systems, the gains are not astronomical, but still impressive. In FIGURE 4 we have gains of approximately $4 \times 10^6$ at range ten meters, and at ten kilometers, $4 \times 10^9$. We note that delivery delays associated with these distances are 1.4 and 45 seconds, respectively. We also note that if more typical propagation loss characteristics ($D^4$) were used [27], the gains of inscribed mass over radiation would be much higher. For example, instead of $4 \times 10^9$ at ten kilometers we would have $4 \times 10^{17}$, and at ten meters, we would gain a factor of one hundred.

Thus, for reasonable receiver aperture sizes and dense but empirically possible mass information density, inscribed mass transport is *much* more efficient than isotropic radiation over point to point links when some delay can be tolerated.

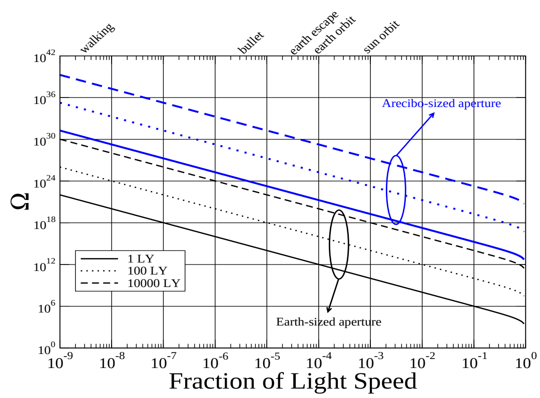


Fig. 3. Energy ratio for free space particles versus mean particle speed using equation (34) for earth-sized and Arecibo-sized sized apertures. The bit per mass density is $\rho = 1.8 \times 10^{24}$bit/kg and the receiver temperature $3°$K.

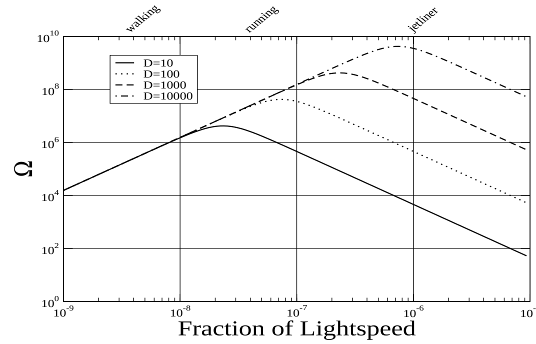


Fig. 4. Energy ratio for artillery problem with a receiver aperture of $R = 0.1$m and distance $D$ in meters versus mean particle speed using equation (35). Mass bit density $\rho = 1.8 \times 10^{24}$bit/kg, receiver temperature $300°$K. $D^2$ propagation loss assumed.

### B. Focused Radiation

Electromagnetic radiation can be directed toward targets through means of a properly constructed antenna. Via Fourier optics [27] we have the fraction of radiated energy captured as

$$G = \frac{1}{4}\left(\frac{RL}{D\lambda}\right)^2 \qquad (36)$$

where $R$ is the receive aperture radius, $L$ the transmit aperture radius, $D$ the range to target and $\lambda$ the radiation wavelength. Assuming apertures, distances and wavelengths such that $G \leq 1$ in equation (36) we have using equation (35) and equation (34)

$$\rho_{\text{terr}} \underset{\text{radiate}}{\overset{\text{write}}{\gtrless}} 4.27 \times 10^{20} \frac{R^2 L^2}{D\lambda^2} \qquad (37)$$

and

$$\rho_{\text{stel}} \underset{\text{radiate}}{\overset{\text{write}}{\gtrless}} 4.36 \times 10^{21} \bar{v}^2 \frac{R^2 L^2}{D^2\lambda^2} \qquad (38)$$

where we assume the terrestrial system receiver has temperature $300°$K and the interstellar receiver has temperature $3°$K.

For a terrestrial system with $1m$ radius receive and transmit apertures, a range of $10m$, and a transmission wavelength of $5.66cm$ (5.3GHz U-NII band) we have a *critical mass information density* $\rho^* = 1.33 \times 10^{22}$ where inscribed mass and radiation are equally efficient. For $0.1m$ radius receive/transmit apertures we have $\rho^* = 1.33 \times 10^{18}$. Likewise, at a range of $1km$ we have $1.33 \times 10^{19}$ and $1.33 \times 10^{15}$ respectively. All these values fall within the range of empirically observed mass information densities.

For interstellar transport with Arecibo-sized receive/transmit apertures with a somewhat arbitrary $1\mu m$ radiation wavelength we have $\rho^* = 2.46 \times 10^{10}\bar{v}^2$ at a range of 1LY and $246\bar{v}^2$ at a range of $10^4$LY – both easily within the range of empirically observed $\rho$. In contrast, for earth-sized apertures, these figures balloon to $1.74 \times 10^{22}\bar{v}^2$ and $8.06 \times 10^{20}\bar{v}^2$. Since mass escape from the solar system requires average speeds on the order of $\bar{v} = 10^{-3}c$, mass information densities much larger than those observed empirically would be necessary.

## VI. Discussion and Conclusion

In the previous sections we have seen that inscribed mass channels can be many many orders of magnitude more efficient than channels which use electromagnetic radiation – even when assumptions are made which favor the radiative channel such as large bandwidth ($\frac{WT}{B} \gg 1$) as well as best case $D^2$ propagation loss in terrestrial systems. The only situation where it might be difficult to make inscribed mass transport more efficient are for what seem heroically large (earth-sized) receive and transmit apertures. Furthermore, from a theoretical perspective, the energy cost of transferring local information to inscribed mass can be made as small as necessary so that no energy penalty need be paid for the inscription process [1], [16], [17].

We have here ignored the benefits of isotropic radiation when broadcasting a single message. However, more careful calculations using reasonable receiver densities [23] show that inscribed mass still has an impressive advantage, even in broadcast situations. We have also ignored the channel characteristics for inscribed mass by essentially assuming that what is sent arrives intact. For terrestrial systems, this is probably not a bad assumption. However, for interstellar transport, a mass packet would be subject to a variety of high energy insults for a long period of time. This issue is important and the subject of ongoing work [19]. However, we note that the relative efficiency of inscribed mass can be at times so enormous, that incredibly high error rates could be tolerated using simple redundancy codes, by sending large numbers of separate messages, or even by encasing the message in a hardened transport carrier.

Finally, for such long range channels, we have skirted the issue of what sort of messages one might want to send, how they might be detected or where they might be sent [28], [29]. The large delays associated with interstellar travel and the seeming fragility of species to cosmic insults suggests that an intelligent sender might construct messages “for posterity” as opposed to for initiating a chat. One might also think of “colonization” as a goal as well [30]. In both regards, one ostensible virtue of inscribed mass channels is that once the message arrives, it is persistent as compared to electromagnetic radiation which is transient and thus must be sent repeatedly in order to assure reception. Of course, constructing mass packets to be hearty, easily detected and/or self replicative seems well outside our current engineering ken. Nonetheless, the notion of mass packet delivery, undertaken initially to examine assumptions about energy tradeoffs in terrestrial communications, does raise interesting questions about terrestrial biological history and perhaps SETI/xenobiological studies as well.

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