Inscribed matter as an energy-efficient means of communication with an extraterrestrial civilization

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It is well known that electromagnetic radiation—radio waves—can in principle be used to communicate over interstellar distances[1,2]. By contrast, sending physical artefacts has seemed extravagantly wasteful of energy, and imagining human travel between the stars even more so[3,4]. The key consideration in earlier work, however, was the perceived need for haste. If extraterrestrial civilizations existed within a few tens of light years, radio could be used for two-way communication on timescales comparable to human lifetimes (or at least the longevities of human institutions). Here we show that if haste is unimportant, sending messages inscribed on some material can be strikingly more energy efficient than communicating by electromagnetic waves. Because messages require protection from cosmic radiation and small messages could be difficult to find among the material clutter near a recipient, 'inscribed matter' is most effective for long archival messages (as opposed to potentially short "we exist" announcements). The results suggest that our initial contact with extraterrestrial civilizations may be more likely to occur through physical artefacts—essentially messages in a bottle—than via electromagnetic communication.

We consider a message of B bits to be sent over a distance D and received by time τ. For inscribed matter we assume the destination is at rest relative to the source, that the mass packet is accelerated with a launcher (as opposed to an on-board engine) and for the moment, that the packet is not decelerated but is 'caught' at its destination. For radiation, the transmission is of duration T, so the entire message is available at the receiver after a delay of $\tau = D/c + T$. We use message delivery energy as a proxy for cost since it represents a required minimum of resources, independent of technological or organizational skill.

The energy required to deliver inscribed matter a distance D by time τ in free space is minimized if the particle is launched at speed $v = D/\tau$. We parameterize acceptable delay by a dimensionless quantity $\delta = c\tau/D$ where $\delta \gtrsim 1$ means that we require the message to be available at a time just greater than the light transit delay, and $\delta \gg 1$ means we can tolerate a long delay. For a message of size B using matter with mass information density of $\tilde{\rho}$ (bits kg^{-1}) we then have energy:

$$E_w = \frac{1}{2}\left[\frac{B}{\tilde{\rho}}\right]\left(\frac{c}{\delta}\right)^2 \tag{1}$$

Notice that we assume messages travel at non-relativistic speeds. Relativistic effects are only important when $v \gtrsim 0.7c$, and by our original assumption, we are willing to accept delays much greater than the light transit time. This point is worth emphasizing, because a perceived need for haste led to the conclusion that delivery of matter over interstellar distances is energetically prohibitive[3,4]. We also note that particle delivery might require overcoming a gravitational potential, but carefully computing such penalties does not greatly affect our main points.

To send the same message of B bits between antennas of equal aperture R separated by distance D requires energy:

$$E_r \geq BN_0 \frac{\lambda^2 D^2}{2\pi^2 R^4} \ln 2 \tag{2}$$

with operating wavelength λ and noise spectral density N_0. This lower bound is derived from information theory and assumes diffraction-limited optics[5,6]. This is a best-case scenario for electromagnetic communication that sidesteps the admittedly interesting questions of preferred frequencies and bandwidths considered by others[1,2,7]. Our energy estimate is conservative because no method of electromagnetic communication can use less energy than is given by equation (2). A full derivation can be found in the Supplementary Information.

We can now define Ω, the radiation-to-inscribed-matter energy ratio, as:

$$\Omega = \frac{E_r}{E_w} \geq \frac{16 \ln 2}{\pi^2}\left[\frac{\tilde{\rho} N_0}{c^2}\right]\left[\frac{\mathcal{D}}{\mathcal{A}}\right]^2 \delta^2 \tag{3}$$

where $\mathcal{A} = 2R/\lambda$ is the normalized antenna aperture and $\mathcal{D} = D/2R$ is the distance between transmitter and receiver in units of antenna aperture. This is our main result. $\Omega > 1$ implies more energy per bit to radiate information than to deliver it via inscribed matter. As expected, Ω increases with $\mathcal{D}$ owing to the unavoidable dispersal of electromagnetic radiation with distance, and decreases with the better collimation afforded by increased antenna aperture $\mathcal{A}$. We also see that relaxing the requirement of haste benefits inscribed matter by a factor δ^2.

How well inscribed matter performs depends on how densely information can be written. A scanning tunnelling microscope (STM) can place an equivalent of about 10^{15} bits per square inch using individual xenon atoms on a nickel substrate[8]. The per bit dimension is then 0.8 nm on a side. Assuming a 10-nm nickel buffer between layers, we obtain a bit density of 1.56×10^{20} bits cm^{-3}, or $\tilde{\rho}_{STM} = 1.8 \times 10^{22}$ bits kg^{-1}. If we could build stable alloys of the lightest solid elements (Li, Be) with arbitrary placement of the atoms, we could achieve $\tilde{\rho}_{LiBe} = 7.5 \times 10^{25}$ bits kg^{-1}. For comparison, the information density of single-stranded RNA (for example, polio virus RNA) is about 3.6×10^{24} bits kg^{-1}. We adopt a conservative $\tilde{\rho} = 10^{22}$ bits kg^{-1} (equivalent to about 1000 nickel atoms per bit) as our reference mass information density.

Message assembly is part of the inscribed-matter energy budget, and even if in theory this assembly energy is zero[9], it is useful to have empirical bounds. As a worst case, message assembly might require construction from individual atoms. Assuming an energy of about 2 eV per bond leads to about 2,000 eV bit^{-1} for assembly of a nickel-based message. Using Solar System escape velocity from Earth orbit (42 km s^{-1}) and $\tilde{\rho} = 10^{22}$ bits kg^{-1}, we find that the launch energy per bit is 5.5×10^5 eV bit^{-1} or 275 times the 2,000 eV bit^{-1} assembly energy. We therefore expect inscription energy cost to be negligible relative to launch energy cost at the speeds required for interstellar delivery. A more complete discussion of these issues can be found in the Supplementary Information.

There are two more potentially serious energy penalties for inscribed matter. The message must be either encoded or shielded to preclude irreparable radiation damage during its journey, and if the message is to await discovery at its destination, some means of deceleration is required for gravitational capture by the target.

To reach a star ten thousand light years away at a speed of $10^{-3}c$, an inscribed-matter packet would endure a trip of ten million years and a variety of insults from the interstellar medium. If, for example, 99% of the bits in a message were randomly erased by cosmic rays, the coding needed to ensure error-free reception requires us to send 100 bits for every bit in the original message[5]. If messages are more fragile, we can also consider shielding. Recent studies[10] show that 800 g cm^{-2} of shielding material could support 10% viability of bacterial spores (*Deinococcus radiodurans*) subject to cosmic radiation for approximately 30 million years. Assuming shield material with an approximately terrestrial average density of 3 g cm^{-3}, 10% survival of a 1 kg information payload incurs a total mass to (surviving) information penalty of roughly 2.4×10^6.

An on-board means of decelerating a message of size B at the destination reduces the efficiency by a factor of $\exp(c/\delta g I_{sp})$, because mass must be expelled as exhaust to brake the craft. The product gI_{sp}, where g is the Earth gravitational acceleration, is just the exhaust velocity of the braking rocket. This parameterization, introducing the specific impulse I_{sp}, is conventional for comparing the efficiencies of different rockets. Values of I_{sp} range from hundreds of seconds for chemical engines to 10^6 seconds for antimatter annihilation engines[11,12]. For $I_{sp} = 2 \times 10^4$ (nuclear electric engine) and $\delta = 1{,}000$, the braking penalty factor $\exp(c/\delta g I_{sp})$ would be 4.6.

In Fig. 1 we provide iso-Ω contours as a function of $\mathscr{D}$ and $\mathscr{A}$ for communications with $\delta = 10^3$ ($\bar{v}$ about seven times larger than solar escape velocity at Earth distance) and $\tilde{\rho} = 10^{22}$ bits kg^{-1}. Points corresponding to examples of receiver apertures and operating wavelengths at various distances are shown. We see that inscribed matter is energetically favoured over a wide range of conditions. For instance, inscribed matter is more efficient than radiation between Arecibo-sized apertures for distances greater than 1.32×10^{12} m ($\mathscr{D} = 4.4 \times 10^9$), about the distance from the Sun to Saturn. Likewise, 10-m optical and 1-m X-ray systems are less efficient than inscribed matter for distances beyond about 0.04 and 2 light years, respectively.

As a concrete example, consider the Voyager spacecraft carrying an analogue recording containing about 10^9 bits of information. The spacecraft has a mass of about 10^3 kg. If Voyager had been fired from a catapult rather than a rocket, its launch energy of 800 J bit^{-1} would make it more efficient than Arecibo-to-Arecibo radio communication for distances beyond about 2,000 light years. Were Voyager carrying three DVD disks (about 10^{11} bits), this 'break-even distance' would be 200 light years. With 100 g of $\tilde{\rho} = 10^{22}$ material, break-even would occur at 2×10^{-3} light years. And if rocket were used rather than a catapult, all break-even distances would be a factor of about nine larger.

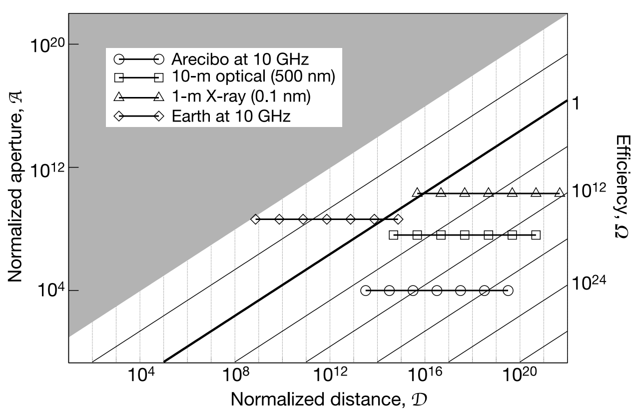

Figure 1 Efficiency of inscribed matter compared to electromagnetic communication. Contours of constant Ω are plotted as a function of $\mathscr{A} = 2R/\lambda$ (a measure of transmit antenna directivity) and $\mathscr{D} = D/2R$ (a measure of receiver power capture) using equation (3). We assume equal-sized transmit and receive apertures, receiver noise temperature 3 K, $\delta = 10^3$ and $\tilde{\rho} = 10^{22}$ bits kg^{-1}. Below and to the right of the line labelled $\Omega = 1$, inscribed mass is a more energetically efficient means of communication. In the shaded region, aperture and distance are such that no additional advantage is conferred by tighter beam collimation—all radiated energy is captured at the target. In this parameterization, isotropic transmission is given by $\mathscr{A} = 1/\pi\sqrt{2}$, the smallest value of ordinate plotted. ($\mathscr{D}$,$\mathscr{A}$) points are also shown for various antenna aperture sizes (Arecibo, $R = 150$ m, an antenna the diameter of the Earth, $R = 6.38 \times 10^6$ m, 10-m optical and 1-m X-ray telescopes) and radiation wavelengths (0.03 m (10 GHz), 500 nm (optical) and 0.1 nm (X-ray)). Target ranges from 1 to 10^6 light years in one-light-year increments are depicted for each case. For reference we note that $\delta = 7{,}143$ at solar escape velocity near Earth (42 km s^{-1}), whereas here we use a speedier $\delta = 10^3$. At the high gains needed for radiation to be competitive with inscribed matter, radio beams do not illuminate many stars, vitiating any 'broadcast advantage' of radiation. A 10-GHZ Arecibo-sized aperture pointed in the plane of our galaxy illuminates about 10^3 stars within 10^4 light years—a small incursion on the inscribed-matter advantage of about 5×10^{15}. Similarly oriented 10-m optical and 1-m X-ray aperture beams are narrow and enjoy no broadcast advantage out to 10^4 light years.

For a 10^4 light year trip, the combined penalty for conservative shielding and deceleration is approximately 10^7, but this is insufficient to negate the very large inscribed-matter advantage over radiation seen in Fig. 1. We have also not accounted for the fact that a radio message must be repeated many times to have a high probability of being received by a destination that may only occasionally be listening. Accounting for this effect would make inscribed matter orders of magnitude more attractive, as shown in the Supplementary Information.

Having shown that writing can use much less energy than radiating leaves us with two practical questions: does sending written messages across interstellar space really confer a practical advantage over radio, and if so, what are the implications for extraterrestrial message search from Earth?

Could the total cost of an effort to communicate across interstellar distances be less using inscribed matter? Equation (3) is a bound on marginal efficiency. That is, Ω is the minimum energy needed to send an additional bit, ignoring the cost of building the infrastructure to send messages by either radiation or inscribed matter. To benefit from the efficiencies promised by equation (3), a civilization must be able to launch messages that can navigate between the stars. It would seem that a simple radio beacon would require fewer resources and thus might be the preferred means for a civilization to announce itself.

Although narrow-band radio beacons could be efficient for short "we exist" messages, if a civilization wants to send more than just a few bits of information a substantial distance across the Galaxy, then it is constrained by physics to build very large antennas—as large as the Earth if using microwave frequencies—or to consider sending a message inscribed on matter. Although we cannot know the actual level of resources needed to build an interstellar communication system, we can say that if long messages are desired, the irreducible expenditure of energy reflected by equation (3) becomes more important and favours inscribed matter.

If interstellar inscribed-matter messages are indeed more efficient, then it is natural to ask where they might be found in our Solar System. Messages designed to await discovery would have to remain in orbits of long-term gravitational stability, or on the surface of objects in such orbits. The stable Lagrange points (L4 and L5) of Jupiter and the Sun, L4 and L5 of the Earth and the Moon, orbits close to the Sun, low-eccentricity orbits in the main asteroid belt[13] and perhaps similar orbits in the Kuiper belt offer such zones of dynamical refuge. The surfaces of various bodies in the inner Solar System are also possibilities.

Any message presumably arrived after the Solar System became habitable (that is, after most of the protoplanetary debris had cleared), so whatever carried the message would be less eroded by impacts than an asteroid. Interplanetary radar could search for objects with anomalously smooth radar signatures. Alternatively, a message could have a retroreflector attached to produce an anomalously large radar cross-section. Of course, an even simpler strategy is to use a powerful radio beam to illuminate these regions and see whether anything answers back. More-active message types (ecological seeds[14] or probes[15]) are also conceivable, but are not necessary to exploit inscribed-matter efficiency.

Our results suggest that carefully searching our own planetary backyard may be as likely to reveal evidence of extraterrestrial civilizations as studying distant stars through telescopes. □

Received 8 April; accepted 16 July 2004; doi:10.1038/nature02884.

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Supplementary Information accompanies the paper on **www.nature.com/nature**.

Acknowledgements We thank G. Foschini, G. Gonzalez, P. Herry, P. Morrison, P. Shor and S. Tournpis for their comments on an earlier version of the manuscript. This work was supported, in part, by the National Science Foundation.

Competing interests statement The authors declare that they have no competing financial interests.

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Spectroscopy of spontaneous spin noise as a probe of spin dynamics and magnetic resonance

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Not all noise in experimental measurements is unwelcome. Certain fundamental noise sources contain valuable information about the system itself—a notable example being the inherent voltage fluctuations (Johnson noise) that exist across any resistor, which allow the temperature to be determined[1,2]. In magnetic systems, fundamental noise can exist in the form of random spin fluctuations[3,4]. For example, statistical fluctuations of N paramagnetic spins should generate measurable noise of order $\sqrt{N}$ spins, even in zero magnetic field[5,6]. Here we exploit this effect to perform perturbation-free magnetic resonance. We use off-resonant Faraday rotation to passively[7,8] detect the magnetization noise in an equilibrium ensemble of paramagnetic alkali atoms; the random fluctuations generate spontaneous spin coherences that precess and decay with the same characteristic energy and timescales as the macroscopic magnetization of an intentionally polarized or driven ensemble. Correlation spectra of the measured spin noise reveal g-factors, nuclear spin, isotope abundance ratios, hyperfine splittings, nuclear moments and spin coherence lifetimes—without having to excite, optically pump or otherwise drive the system away from thermal equilibrium. These noise signatures scale inversely with interaction volume, suggesting a possible route towards non-perturbative, sourceless magnetic resonance of small systems.

The fluctuation–dissipation theorem states that the response of a system to an external perturbation (that is, the susceptibility) can be described by the spectrum of fluctuations exhibited by the system in thermal equilibrium[9]. In magnetic systems, $\sqrt{N}$ fluctuations in an ensemble of N undriven nuclear spins has been observed[6], as predicted by Bloch[5] in 1946. Fundamental magnetic fluctuations of thermal (and quantum) origin have since been identified in, for example, spin glasses[10], hard-disk magnetoresistive heads[11], and in the magnetic noise spectrum of antiferromagnetic particles[12]. Optical techniques have identified the presence of stochastic spin fluctuations in atomic systems[4,13–16], and notably, fluctuations corresponding to very few spins—and perhaps even single spins—are evidenced by ultrasensitive cantilevers[17] and scanning tunnelling microscopes[18,19], respectively. In other disciplines, thermal noise in nanomechanical resonators[20] and recent correlation spectra of thermal acoustic vibrations suggest a means for 'sourceless ultrasonics'[21]. Here we investigate the detailed spectroscopy of spin noise to perform perturbation-free magnetic resonance. We study ground-state magnetization fluctuations in a classical ensemble of uncorrelated paramagnetic spins in thermal equilibrium, realized in atomic alkali vapours. Random spin fluctuations and their associated coherences reveal the complete magnetic structure of the atomic $^2S_{1/2}$ ground state, including hyperfine, Zeeman and nuclear moment effects. Historically, this information is obtained with conventional magnetic resonance techniques (optical pumping and/or radio-frequency excitation)[22–24], which necessarily perturb the spin ensemble away from thermal equilibrium.

Figure 1a shows a diagram of our experiment. A Ti:sapphire ring laser (~8 GHz linewidth), detuned from any atomic absorption, is linearly polarized and focused through a cell containing a

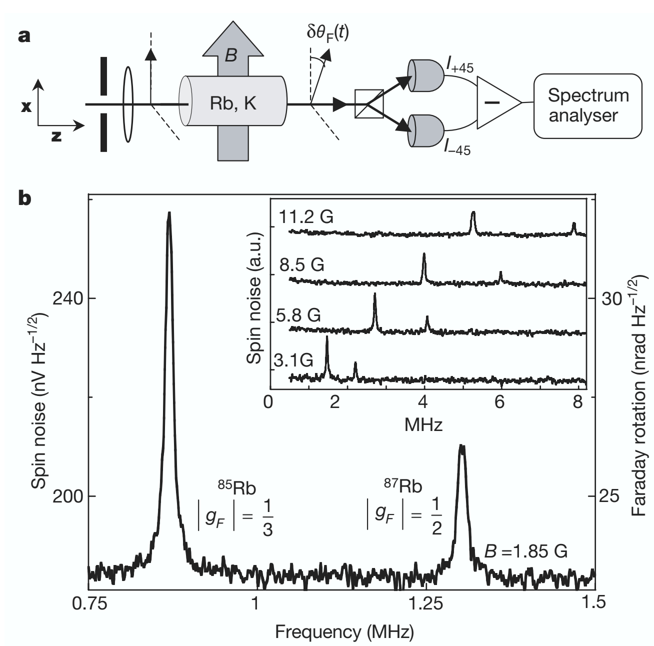

Figure 1 Spontaneous spin noise in Rb or K vapour, probed via Faraday rotation. **a**, Experimental schematic. Ground-state stochastic spin fluctuations $\delta M_z(t)$ impart polarization fluctuations $\delta\theta_F(t)$ on the detuned probe laser. **b**, Measured spectrum of spin (Faraday rotation) noise from Rb vapour at temperature $T = 369$ K and magnetic field $B = 1.85$ G, showing spontaneous spin coherence peaks from ^{85}Rb and ^{87}Rb. The data are given in units of root-mean-square (r.m.s.) spectral density of voltage fluctuations (nV Hz$^{-1/2}$) measured in the photodiode bridge, and also by the r.m.s. spectral density of Faraday rotation fluctuations (nrad Hz$^{-1/2}$). The noise floor is determined primarily by photon shot noise. The laser is detuned $\Delta_{D1} = 25$ GHz from the D1 transition ($5^2S_{1/2}$ to $5^2P_{1/2}$, ~794.8 nm), ensuring negligible absorption. Inset: the ^{85}Rb and ^{87}Rb spin noise peaks measured at $\Delta_{D2} = 20$ GHz from the D2 transition ($5^2S_{1/2}$ to $5^2P_{3/2}$, ~780 nm). The magnetic field B is incremented in steps of 2.7 G, and $T = 369$ K. Plots offset vertically for clarity. a.u., arbitrary units.