Will ET Write or Radiate?

(the unreasonable efficiency of
messages in a bottle)

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A truck filled with storage media, driven across town, is a very reliable high bit rate channel.

–*Comm. Theory Collective Subconscious*

EPIPHANY: wireless research gone wild

- **Interference is bad**
  - Mutual interference is a network killer
- **Mobility is good**
  - Can often tolerate delay
  - Channel especially good when nearby
- **Storage density is increasing**
  - Faster than Moore!

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GO POSTAL

Forget Radio! **Write** message down! **Toss** it to recipient!

Completely ridiculous!!

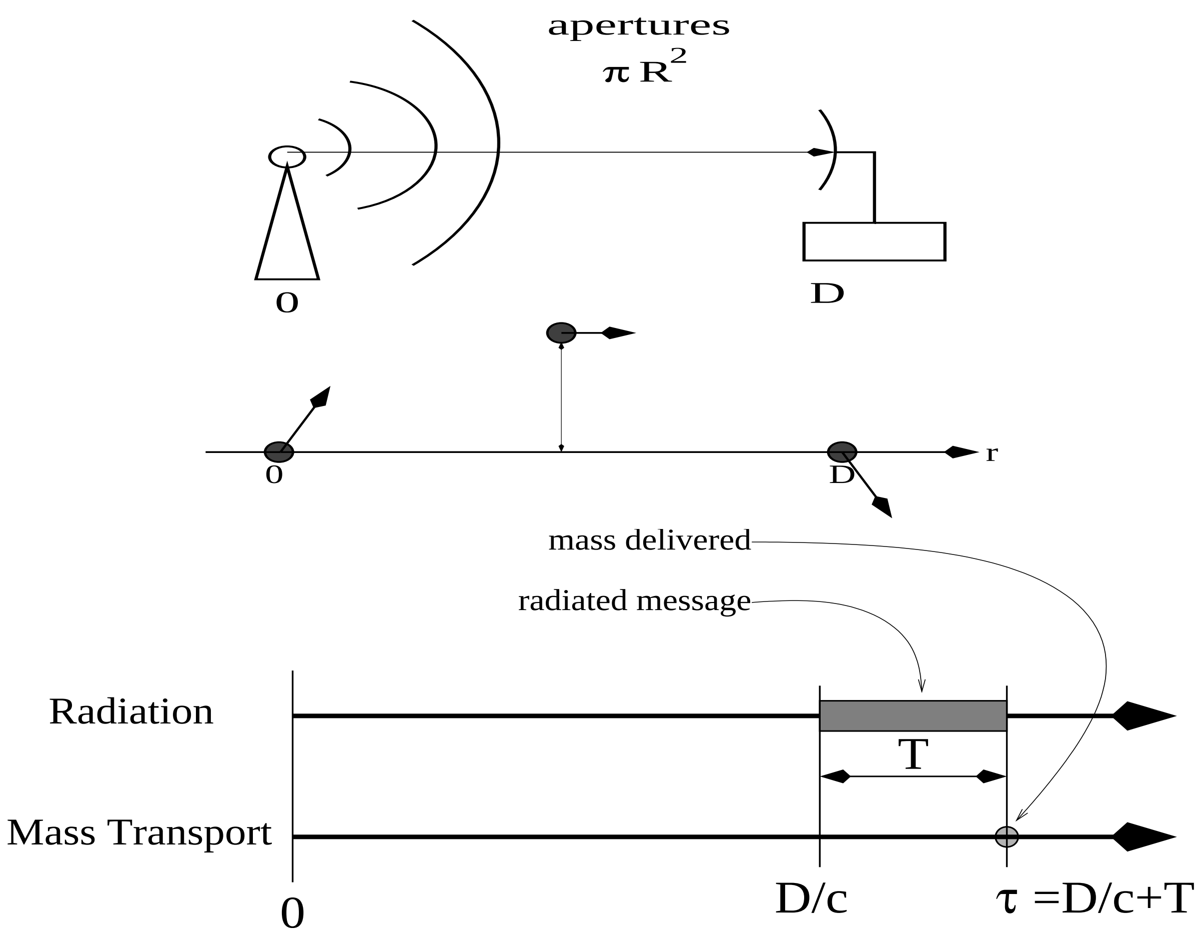
(right?)

Tossing Is Not Easily Dismissed

- **NYC/Boston Matter Transport Energy**
  - 200 miles at 20 miles per gallon
  - 1.2×10^8 Joules per gallon
  - 100kg DVDs: ≈ 250000 **bits/joule**
- **Equivalent Radiation Energy**
  - Satellite: 5660 **bits/joule**
    (3.5×10^4km uplink, D^2 propagation, 1m^2 dish)
  - Terrestrial (320km, D^4 propagation): MUCH lower efficiency

But ad hoc comparisons are unsatisfying ...

A Little Analytic Rigor



Radiation Energy Requirements

- Energy capture

$$\nu(D) = \frac{AG}{4\pi D^2}$$

- **Shannon Capacity:**

$$B = CT = TW \log_2\left(\frac{P\nu(D)}{N_0 W} + 1\right)$$

- $E_r = PT$:

$$E_r = BN_0 \frac{4\pi D^2}{AG} \frac{TW}{B} \left[2^{\frac{B}{TW}} - 1\right]$$

- Large TW:

$$\boxed{E_r \geq BN_0 \left(\frac{4\pi D^2}{AG}\right) \ln 2}$$

Jensen's Inequality & Rocket Science

- Average velocity:

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

- Minimum imparted energy subject to $\bar{v} = \frac{D}{\tau}$:

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

$$\max_t h(v(t)) \geq E[h(v(t))]$$

- Put it all together for convex $h()$:

$$\mathcal{E}^* = \min_{v()} \max_t h(v(t)) \geq \min_{v()} \underbrace{E[h(v(t))] \geq h(\bar{v})}_{\text{Jensen}}$$

with equality iff $v(t)$ is constant $= \bar{v}$

Minimum Transport Energy

- GIVEN: $h()$ and $\bar{v}$

$$\mathcal{E}^* = h(\bar{v})$$

- **Relativistic:** $h(v) = mc^2 \left(\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} - 1 \right)$

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

- **Non-relativistic:** $h(v) \approx \frac{1}{2} m v^2$

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

But What About Gravity?

- $q(x)$ potential energy:

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

- Energy minimization:

$$\mathcal{E}^* = \min_{x()} \max_{t} \mathcal{E}(t, x(t), v(t)) \geq \min_{x()} \frac{1}{\tau} \int_0^{\tau} \mathcal{E}(t, x(t), v(t)) dt$$

- Calculus of variations:

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

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

Potential Field Results

- Non-relativistic:

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

- $q'(x)$ is force at position x: $\rightarrow$ "free fall"
- Freefall? $\rightarrow$ $\mathcal{E}(t) =$ constant
- $\mathcal{E}(t)$ constant $\rightarrow$ minimization satisfied with equality, so ...

Potential Fields Results

- Low speed:

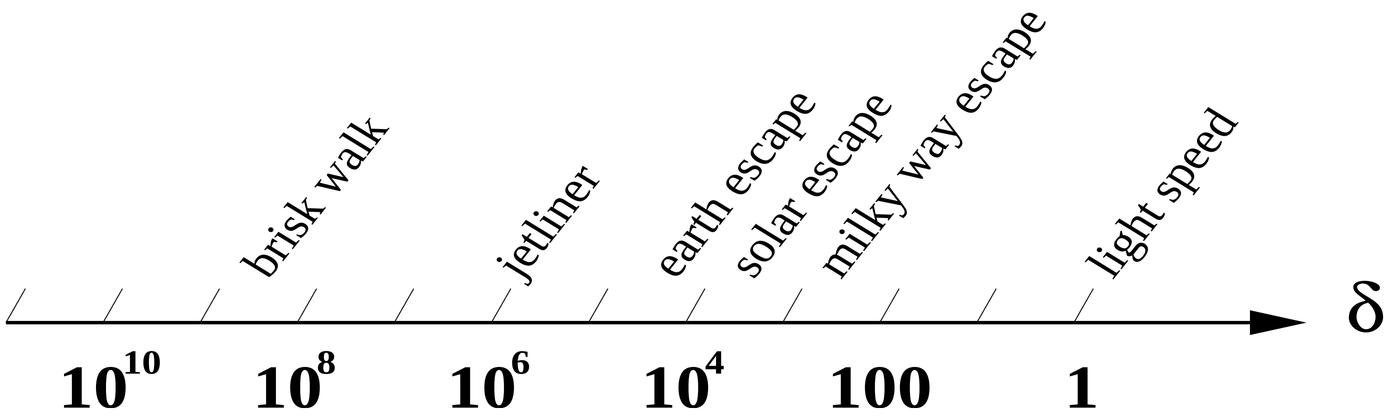
$$m\ddot{x} = q'(x)$$

- $q'(x)$ is force at position x: $\rightarrow$ "free fall"
- Freefall? $\rightarrow \mathcal{E}(t) = $ constant
- $\mathcal{E}(t)$ constant $\rightarrow$ minimization satisfied with equality, so ...

Inscribed Matter Energy Requirements

- Message size B bits, mass information density $\tilde{\rho}$ bits/kg, Delay factor δ

$$E_w = \frac{1}{2}\frac{B}{\tilde{\rho}}\bar{v}^2 = \frac{1}{2}\frac{B}{\tilde{\rho}}\left(\frac{c}{\delta}\right)^2$$



- **Artillery:** adds a factor of 2 to energy
- **Escape:** small penalty if $\bar{v} > 2 \times$ escape velocity

Radiation to Transport Energy Ratio

$$\Omega \equiv \frac{E_r}{E_w}$$

$$\text{Normalized Aperture} \equiv \mathcal{A} = \tfrac{2R}{\lambda}$$
$$\text{Normalized Distance} \equiv \mathcal{D} = \tfrac{D}{2R}$$

$$\Rightarrow \boxed{\Omega \geq \left[\frac{\tilde{\rho} N_0}{c^2}\right] \left[\frac{8}{\pi^2}\left(\frac{\mathcal{D}}{\mathcal{A}}\right)^2\right] (2\ln 2)\delta^2} \Leftarrow$$

Equal Receiver/Transmitter Apertures

Information Density, $\tilde{\rho}$

How About Black Holes?

- Schwarzschild Radius: $r = 2GM/c^2 = 1.5X10^{-27}M$
- Info content goes as event horizon *surface area*: $10^{72}r^2$ bits

$$\tilde{\rho} = 1.5 \times 10^{45} r \text{ bits/kg}$$

- Microhole (1μm radius): 1.5×10^{39} bits/kg
- Donut-hole sized hole (1cm radius): 1.5×10^{43} bits/kg

A wee bit impractical?

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VERY antisocial!

Empirical Mass Information Densities I

Voyager Spacecraft: 10^6 bits/kg

Empirical Mass Information Densities II

- **20 lb paper** @ 1000dpi: 2×10^{10} bits/kg
- **DVD**: 3×10^{12} bits/kg
- **Magnetic Storage** with FeO_2: 2×10^{17} bits/kg
- **Optical Lithography** with SiO_2: 3.85×10^{18} bits/kg
- **E-beam Lithography** with SiO_2: 1.54×10^{21} bits/kg
- **STM** with Xe on Ni: 1.74×10^{22} bits/kg
- **RNA**: 3.6×10^{24} bits/kg
- **Li + Be**: 7.5×10^{25} bits/kg

Radiation

vs.

Inscribed Matter

Terrestrial Artillery vs. Radiation

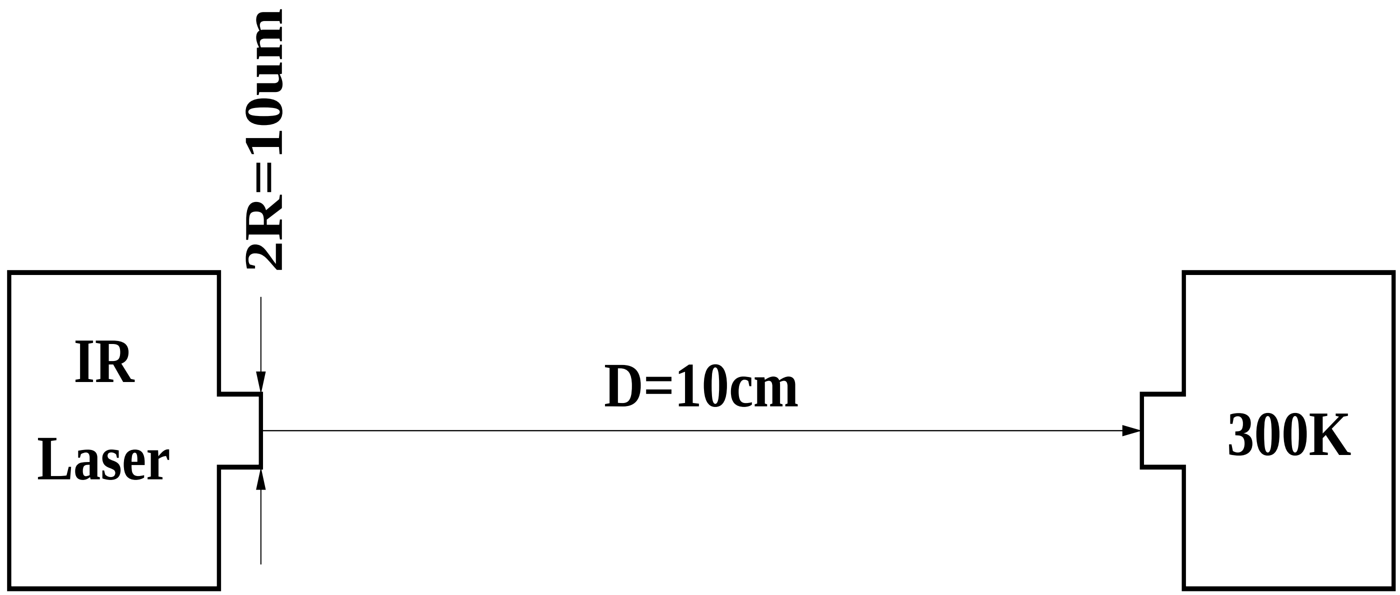
$\tilde{\rho} = 3 \times 10^{24}$, 1 GHz Carrier, $R = 5$cm, Temperature 300K

Range (meters)	Transit Time	Ω
10	1.43 sec	1.3×10^7
100	4.5 sec	1.3×10^8
10^3	14.3 sec	1.3×10^9
10^4	45 sec	1.3×10^{10}

Aside: $\approx$ 4 minutes between NYC and Boston ballistically (320km).

Chip to Chip Laser Links

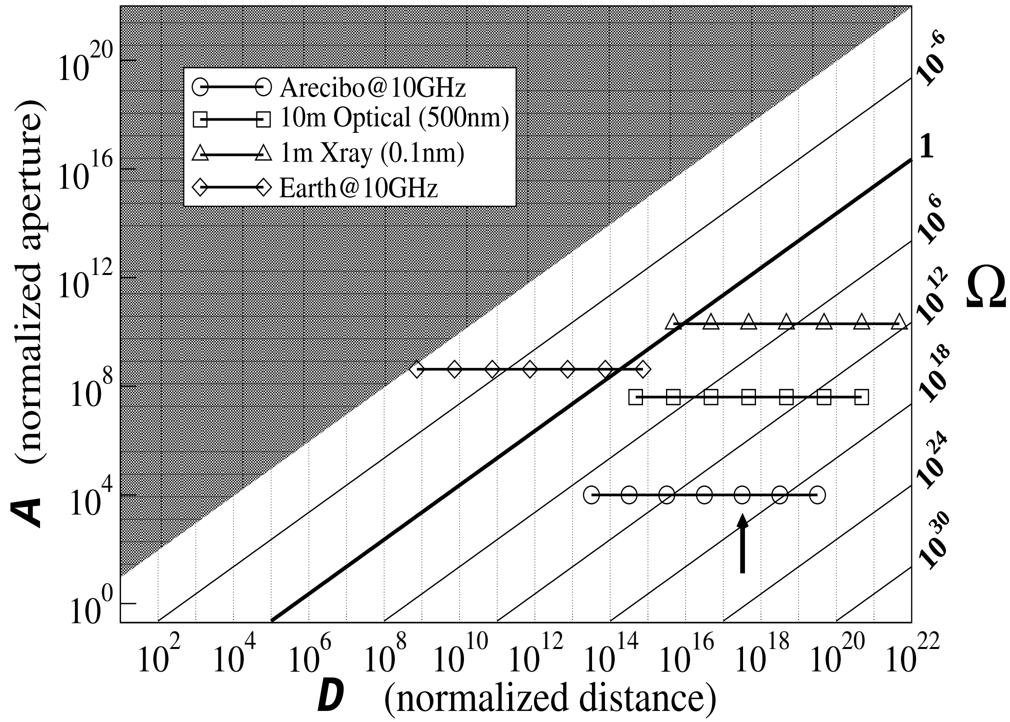
$\delta = 10^9, \lambda = 1\mu m$



Magnetic chits: $\Omega \geq 10^4$

STM inscribed chits: $\Omega \geq 5 \times 10^8$

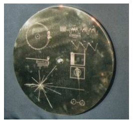
Interstellar



($\tilde{\rho} = 10^{22}$, $\delta = 10^3$, Temperature 3K)

$\longrightarrow$ 10k LY, Arecibo-Arecibo: $\Omega \geq 5 \times 10^{15}$

– Radiation/Matter: (2 megaton blast) / (Shelve 5 lb sugar bag)



Voyager

- 10^9 bit payload
- 900 kg mass
- Catapult launch: about 800 joules/bit

Breakeven Distance: $\approx$ 2000 light years

- Asides:
  - ETA nearest star: $\approx$ 100 kilo-years
  - Rocket Launch: distance up $\times 9$.
  - Use 3 DVDs (instead of gold disc): distance down $\times 10$
  - Use 1 gram of "RNA": distance down $\times 10^6$ ($\approx 1/4000$ distance to nearest star)

Physics Has Spoken

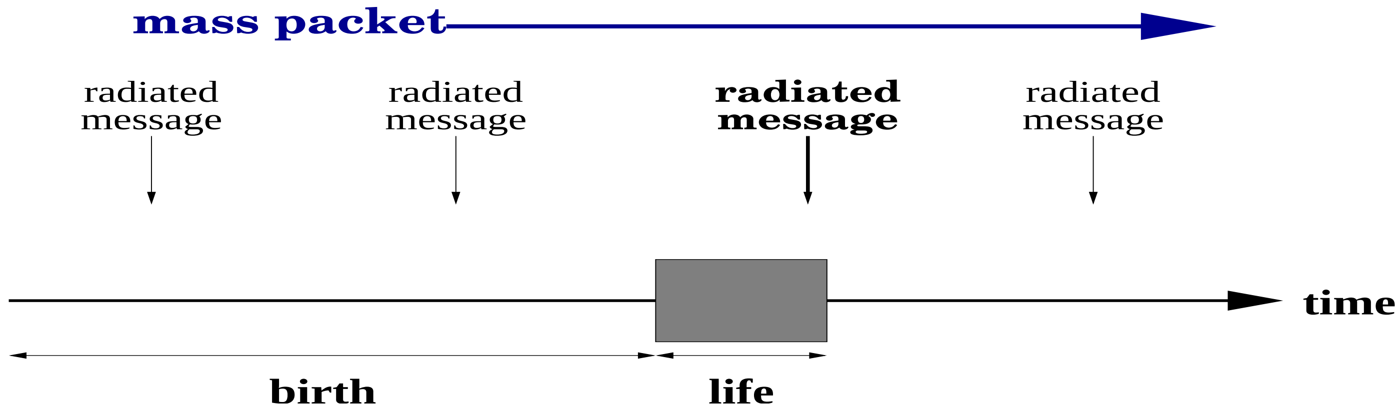
Theoretically, matter is *stunningly* more energy-efficient than radiation

But what about ...

Matter and Radiation Penalties

- **Radiation**
  - Impermanence and Repetition
- **Matter**
  - Broadcast
  - Inscription Energy
  - Deceleration At Target
  - Navigation
  - Preservation
  - Advertisement

Matter Persists – Radiation Vanishes



- Civilization Birth Rate: $\alpha = 1/10^9$ per year
- Civilization Extinction Rate: $\beta = 1/10^6$ per year
- Success criterion $0 \leq \Phi \leq 1$
- **How many radiated repetitions?**
  - $\Phi = 0.99 \rightarrow 2 \times 10^5$
  - $\Phi = 0.9999 \rightarrow 2 \times 10^7$

Is Radiation Better for Broadcast?

Radiation illuminates many → matter penalty

- Milky Way stellar density: 2.8×10^{-2} stars (LY)$^{-3}$
- Spherical galaxy, Arecibo receiver, 10^{22} bits/kg, $\delta = 10^3$
  - $R = 10^4$ LY: 1.13×10^{11} stars (but $\Omega \geq 10^{25}$)
  - $R = 10^6$ LY: 1.13×10^{17} stars (but $\Omega \geq 10^{29}$)
  - $R = 10^{11}$ LY: 1.13×10^{32} stars (but $\Omega \geq 10^{39}$)
  - **Visible Universe:** $R = 1.3 \times 10^{10}$ LY

No, inscribed matter still wins!

Inscription Energy/Speed

- **Matter Inscription/Readout Energy and Time**
  - Can be reversible and abitrarily fast (R. Landauer)
- **Empirical energy calc:**
  - 60000 ATP/second for 20 minutes: 4639 Kbase of E-coli
  - 8×10^{-20}J per ATP molecule
  - 6.2×10^{-19}J bit^{-1} (≈ 4 eV bit^{-1}).
  - E^* at earth escape: 1.68×10^{-17} J bit^{-1}.

Construction energy probably not a problem

Parking the Package

- Assume exhaust braking
- Energy penalty (excess mass): $e^{\frac{c}{\delta g I_{sp}}}$
- $I_{sp} \equiv$ Specific Impulse
  - Chemical: 10^2
  - Nuclear Electric: 10^4
  - Fusion: 10^6
- $I_{sp} = 20,000$, $\delta = 1000 \rightarrow$ **penalty** 4.6
- $\delta = 100$ or $I_{sp} = 2000 \rightarrow$ **penalty** 4.4×10^6

Gravitational Perturbations

Angular Deflection: $\theta \approx \frac{2MG}{v_0^2 y_0}$ (radians)

- $M = 2 \times 10^{30}$kg (solar)
- $v_0 = c/1000$
- Stellar Density: 2.8×10^{-2} stars $(\mathrm{LY})^{-3}$
- 10kLY trip mean miss distance: ≈ 0.14LY

Aim not a big problem

Cosmic Insults

- **Insults:**
  - High energy particle bombardment
  - Heating (diffusion)
  - Ion tracks, dislocations, subatomic cascades
- **Shielding:**
  - 10 million years at 10% bacteria viability: 3 m radius rock (3g cm^{-3} density)
  - **penalty:** 3.4×10^6
- **Clever Composition, Coding and Correction?**
  - need better channel characterization

Message Advertisement?

Solar Space is BIG

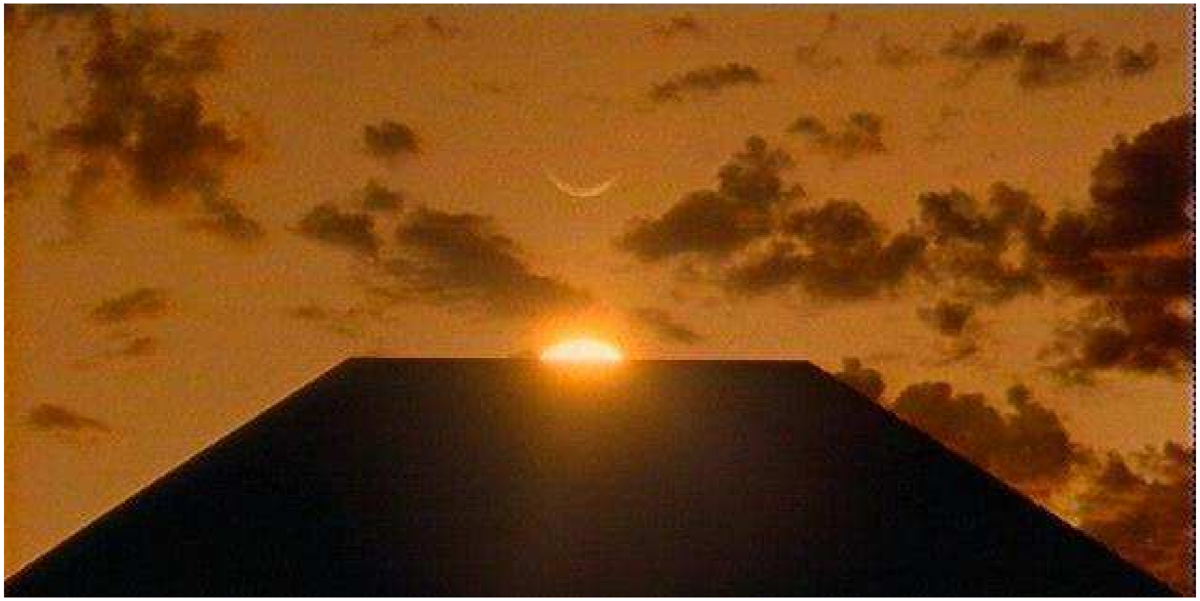
Big Rock?

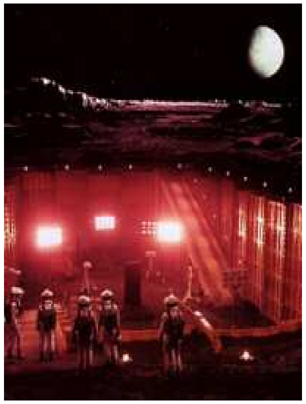
Somewhat antisocial

Odd Rock?

Seeded Comet?

Active Probe?





Life Boat?

Noah's micro-ark?

CONCLUSION

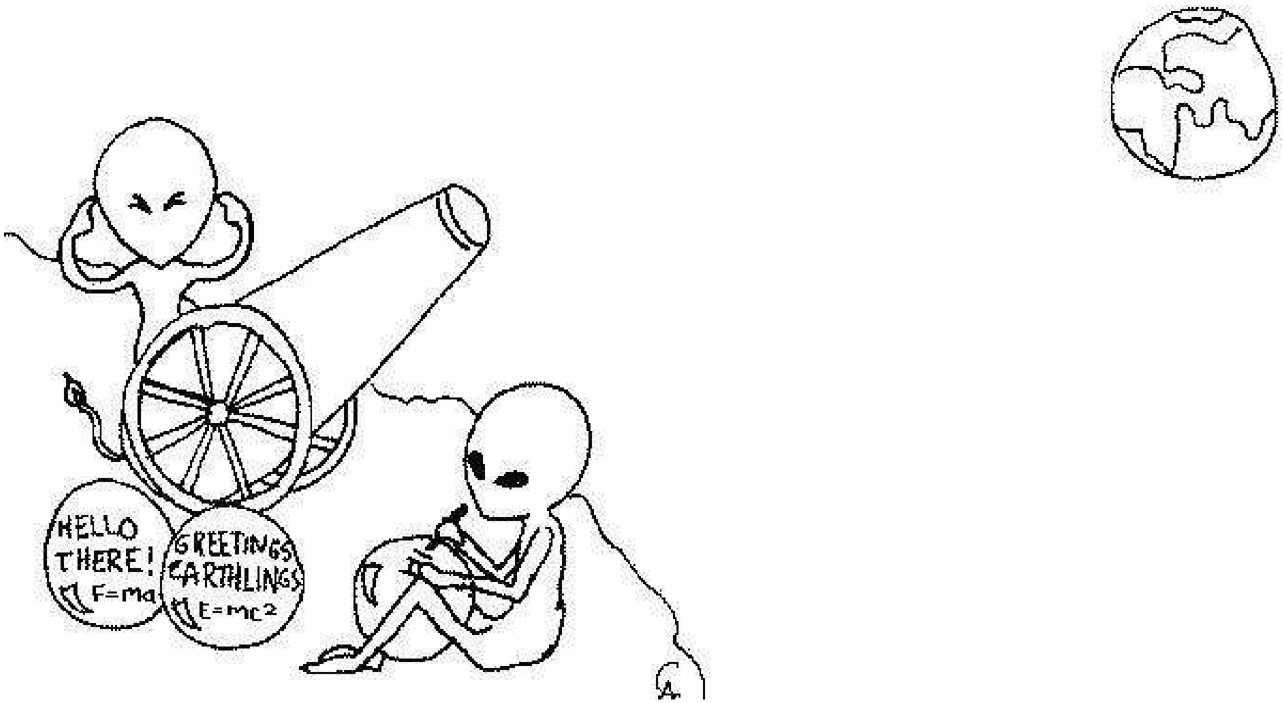
IF: energy important & delay acceptable

THEN: inscribed matter messaging is efficient

- Terrestrial
  - FedEx and Netflix
- Chip-to-chip or mote-to-mote
  - smart dust tossing inscribed dust
- Biological systems
  - construction/dispersal cost for messenger molecules

And perhaps most interesting ...

ET Might Write, Not Radiate



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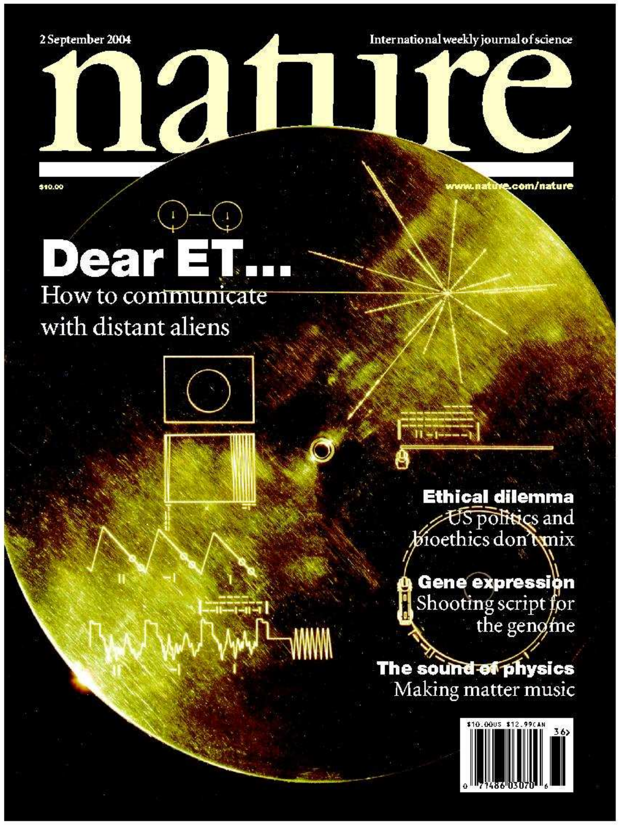

Nature 431, pp.47–49, September 2, 2004

Web Site: http://www.winlab.rutgers.edu/∼crose/cgi-bin/cosmic16.html