ON THE DETECTABILITY OF ANTIMATTER PROPULSION SPACECRAFT

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Abstract. It is shown that the NASA Gamma-Ray Observatory will be able to detect large interstellar spacecraft at distances up to $\sim$ 300 pc by the γ-ray emission from the propulsion system alone. The distance limit is set by the possibility of recognizing such objects by their proper motions.

1. Introduction

The classic method in the search for extraterrestrial intelligence (SETI) is the detection of radio signals emanating from the ETI (Cocconi and Morrison, 1959). Unless radio signals are deliberately transmitted towards the Earth, this approach relies on interception of the ETI's own radio traffic. However, it has been suggested (Wilson, 1948) that other technologies may be preferable for interstellar communication, such as closed guided-channel quantum particle counting techniques, which are not open to interception. It is therefore necessary to consider alternative approaches to SETI.

One class of alternative methods involves detection of alien artefacts (Bracewell, 1960). In this paper we will consider the possibility of detecting the spacecraft which ETI might use for interstellar travel. This work rests on the assumption that modes of interstellar travel will be those recently advocated for terrestrial use by several proponents of space exploration, and in particular that no more efficient fuel will be discovered than antimatter, the most efficient presently known fuel. We will consider detection of the γ-rays from the antimatter annihilation process.

Questions of the plausibility of interstellar travel will not be addressed here, since both proponents and sceptics rely on considerations of alien psychology and economics, the nature of which are utterly unknown. We believe that this argument can only be settled empirically, by the detection or otherwise of interstellar spacecraft.

Detectability of γ-ray emission from spacecraft powered by nuclear fusion, such as the proposed DAEDALUS project (Bond and Martin, 1978), will not be considered here. The propulsion of such spacecraft is much less efficient than antimatter propulsion, making it perhaps less likely that they will be practicable for interstellar travel on the large scale necessary for detectability.

Other unorthodox SETI strategies are reviewed by Freitas (1985).

2. Constraints on Detection of γ-Rays From Interstellar Spacecraft

All proposed interstellar spacecraft designs rely on propulsion mechanisms which produce copious quantities of γ-rays. Even in designs which rely on the trapping of these

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γ-rays to provide thrust, a substantial fraction of them will escape and may be observed. The propulsion mechanisms will be discussed in the two following sections. Here we will consider the prospective limits on γ-ray detection.

The most obvious limit is that imposed by the sensitivity of the γ-ray detector. Since there is no method of predicting the likely size of an alien spacecraft, we note that it is obvious that sufficiently large spacecraft will be detected, i.e., the limit on detector sensitivity is equivalent to a lower limit on the size of the spacecraft. We will be interested in γ-ray energies of ~ 0.5 MeV and of ~ 100 MeV. Very sensitive detectors of these energies will be flown in the NASA Gamma-Ray Observatory (GRO) to be launched in 1988. Of the GRO experiments, the Energetic Gamma-Ray Telescope (EGRET) will have a threshold point source sensitivity of $\sim 5 \times 10^{-8}$ photons cm^{-2} s^{-1} at energies > 20 MeV, while the Burst and Transient Source Experiment (BATSE) will have a maximum sensitivity of $\sim 10^{-5}$ photons cm^{-2} s^{-1} at ~ 500 keV (Kurfess, 1985; Morris, 1985).

Interstellar spacecraft as γ-ray sources will be most easily recognized by their proper motions. Their velocities, being substantial fractions of the velocity of light, will be at least 100 times as large as the highest velocities characteristic of normal astronomical objects. For spacecraft of sufficient size, the poor angular resolution of current γ-ray telescopes imposes a limit on identification rather than detection. Of the GRO instruments EGRET will have an angular resolution of $1\overset{\circ}{.}6$ at 100 MeV, while the best possible resolution of BATSE will be $0\overset{\circ}{.}5$ (Kurfess, 1985; Morris, 1985). In the most favorable circumstances (purely tangential velocity close to c; observations made over the $\lesssim 10$ yr lifetime of GRO) these resolutions will be able to detect the motion of spacecraft at distances of ~ 100 pc and ~ 300 pc, respectively. The implementation of the proposed interplanetary γ-ray satellite network (Hurley, 1983) should permit the achievement of much higher resolutions for brighter sources.

The subject of γ-ray source proper motions has recieved little attention, owing to the poor resolutions achieved. Proper motions have only been measured for lower-frequency sources identified with γ-ray sources; thus proper motions ranging from $0\overset{''}{.}37$ to $1\overset{''}{.}4$ yr^{-1} have been proposed for the optical counterpart of the peculiar source Geminga (Bloemen, 1984; Djorgovski and Kulkarni, 1985). Interstellar spacecraft ought to show much larger motions. The corollary is that, in principle, any γ-ray source showing a high proper motion should be regarded as a possible spacecraft candidate.

3. $\mathrm{p\bar{p}}$ Propulsion

3.1. Spacecraft parameters

Proton-antiproton ($\mathrm{p\bar{p}}$) annihilation may be represented as follows (Agnew *et al.*, 1960)

$$\begin{aligned} \mathrm{p} + \bar{\mathrm{p}} &\to m\pi^0 + n(\pi^+ + \pi^-) \\ &\quad\ \to 2\gamma \qquad\ \to \mu^\pm \to e^\pm \to 2\gamma \text{ per } e^+ , \end{aligned} \tag{1}$$

where $3 \leq 2n + m < 7$. The contributors to Papaillou (1975) and Forward (1976, 1980) have proposed that the charged pions may be directed electromagnetically in order to provide thrust to propel a spacecraft (the most efficient way to do this is to use them to heat and eject a large reaction mass of ordinary matter; Dipprey, 1975). The neutral pions are expected to decay very rapidly, and the resulting γ-ray photons to escape. Such a spacecraft will therefore radiate a large number of photons with energies mainly in the range 50–200 MeV. Self-absorption of these photons by e^-e^+ pair production and other mechanisms (Cavallo and Rees, 1977) is expected to be negligible.

Whether or not the low-energy (~ 0.511 MeV) photons from the e^-e^+ annihilation will escape appears to depend upon the configuration of the reaction mass, and thus upon unknowable details of the spacecraft design. Similarly, synchrotron radiation at centimeter wavelengths is expected to result from the motion of the charged particles in the magnetic fields, and copious X-ray emission may arise if they are stopped by the spacecraft's structural materials, but neither of these effects can be quantified readily.

We will attempt to answer the question of what kind of spacecraft will be detectable by its proper motion (Section 2). The number of photons radiated will depend firstly on the mass M of antimatter consumed. Cassenti (1982) has shown that M obeys

$$\frac{2M}{M_{\rm PL}} = \frac{1}{\eta}\,\frac{\gamma_e - 1}{\gamma_e - \zeta}\,\exp\left\{\frac{\theta}{\left\{(1-\zeta)\dfrac{\gamma_e-1}{\gamma_e-\zeta}\left[(2-\dfrac{\gamma_e-1}{\gamma_e-\zeta}(1+\zeta)\right]\right\}^{1/2} + \dfrac{\gamma_e-1}{\gamma_e-\zeta}\,\zeta} - 1\right\}, \tag{2}$$

where θ, the velocity parameter, is defined in terms of the spacecraft's velocity v seen from rest by

$$\theta = \tanh^{-1} v/c \tag{3}$$

and given by

$$\theta = 1 - \frac{(1-\zeta)\,[\gamma_e - (\gamma_e^2 - 1)^{1/2}]}{\gamma_e - \zeta}\ln\frac{M_{\rm TOT}}{M_{\rm PL}}\,, \tag{4}$$

where η is the efficiency of conversion, γ_e is the relativistic γ factor of the exhaust velocity v_e in the spacecraft frame, ζ is the fraction of the annihilated mass $2M$ which is in the form of massless particles, $M_{\rm PL}$ is the payload mass, and $M_{\rm TOT}$ is the total initial mass of the spacecraft, including the reaction mass $M_{\rm R}$ given by

$$\frac{M_{\rm R}}{2M} = \eta\,\frac{1-\zeta}{\gamma_e - 1}\,. \tag{5}$$

Cassenti (1982) also showed that the value of M is minimized when $\zeta = 0$, and that the $p\bar{p}$ rocket comes closest to achieving this, since if only the π^0 decay γ-rays escape we have $\zeta \sim 0.2$. A reasonable value for η is $\sim 40\%$ (Morgan, 1982).

Note that Equations (2)–(5) refer to a single-stage rocket. Spacecraft which must decelerate on arrival will require a *payload* which is equal to $M_{\rm TOT}$, and so on for further stages.

3.2. Detectability of Photons from π^0 Decay

Assuming that a mass of M of antihydrogen is annihilated steadily over a time τ and that the photons are radiated isotropically, the number of photons from π^0 decay available to an observer r cm away will be

$$n_\gamma = \frac{2mN_A M}{4\pi r^2 \tau} \text{ cm}^{-2}\text{ s}^{-1}, \tag{6}$$

where $N_A = 6.022 \times 10^{23}$ and m (Equation (1)) will be taken to be 2. Assuming r to be 100 pc, beyond which the spacecraft cannot be detected by its proper motion, and assuming the EGRET detectability limit of $> 5 \times 10^8$ cm^{-2} s^{-1}, we clearly see that the inequality

$$\frac{M}{\tau} > 2.5 \times 10^4 \text{ ton s}^{-1} \tag{7}$$

must be satisfied for detection to be feasible.

Note that τ need not be a single interval, but might be split up into any number of separate, shorter periods. Due to the difficulties of firing a $\bar{\text{p}}$ beam at the reaction mass (Morgan, 1982) it may prove preferable to invert the procedure by emplacing a mass of antimatter and injecting hydrogen onto it. Such a spacecraft would accelerate in a series of short pulses. The burn time τ is related to the velocity attained by

$$\tau = \frac{c\theta}{a}, \tag{8}$$

where a is the acceleration required.

There is no obvious way of deriving 'plausible' values of M and τ, in the total absence of information about ETI. Two missions which yield values of M and τ for the first stage which satisfy (7) are described in Table I (A and C). It is clearly idle to speculate what purposes such missions might serve. However, for illustrative purposes we will compare them to possible terrestrial undertakings. Mission A, in which a 3.6×10^8 ton payload

TABLE I

Antimatter propulsion spacecraft detectable by GRO

Title	Propulsion	No. of stages	Payload mass M_{PL} (ton)	Total mass M_{TOT} (ton)	Antimatter mass M (ton)	Exhaust velocity v_e/c (V)	Acceleration a, g	Final velocity v/c (V)	Total burn time τ, days
A	$p\bar{p}$	4	3.6×10^8	3.7×10^{12}	1.3×10^{12}	0.683	1	0.9	521
B	e^-e^+	4	6.6×10^8	9.3×10^{12}	4.5×10^{12}	1.0			
C	$p\bar{p}$	2	6.0×10^8	7.5×10^{10}	2.6×10^{10}	0.683	50	0.9	10.4
D	e^-e^+	2	2.5×10^8	1.9×10^{11}	9.0×10^{10}	1.0			

is accelerated at one g to $0.9c$ in 521 days total burn time, with the capability to fire four stages, might be a mission to colonize an extrasolar planet (cf. the 'world ship' of Dyson, 1968), with an option to return. Mission C, in which a larger payload is accelerated to the same velocity and decelerated at the same rate on arrival, might serve for the one-way bulk transport of raw material (perhaps for the purpose of 'interstellar engineering' as adumbrated by Kardashev, 1964). These objects are on the margin of detectability by GRO; to be clearly detected and identified, such spacecraft must be either larger, closer or more rapidly accelerated.

4. e^-e^+ Propulsion

4.1. Spacecraft Parameters

Propulsion of a spacecraft by e^-e^+ annihilation is much less efficient in its use of antimatter than $p\bar{p}$ propulsion (Cassenti, 1982). However, positrons are much easier to produce than antiprotons. The earliest proposed antimatter propulsion spacecraft was powered by e^-e^+ annihilation (Sanger, 1963); the problem the problem of directing the 0.511 MeV photons (Equation (1)) to produce thrust was to be overcome by the use of dense electron-gas mirrors. The efficiency obtainable in this way is probably $< 10\%$, so that most of the photons produced will escape.

Such a spacecraft will obey Equations (2)–(5) with $\zeta = 1$ and $v_e = c$, since the exhaust is composed entirely of photons.

4.2. Detectability of e^-e^+ Annihilation Photons

For e^-e^+ propulsion spacecraft Equation (6) is replaced by

$$n_\gamma = \frac{M}{4\pi r^2 \tau m_e} \text{ cm}^{-2}\text{ s}^{-1} . \tag{9}$$

Assuming isotropic radiation (but see below) and the BATSE sensitivity of 10^{-5} photons $\text{cm}^{-2}\text{ s}^{-1}$ at ~ 0.5 MeV, we find that the inequality

$$\frac{M}{\tau} > 10^5 \text{ ton s}^{-1} \tag{10}$$

must be satisfied. In Table I we give the parameters of two missions (B and D) which marginally obey (10) and which fulfil the same objectives as $p\bar{p}$ missions A and C.

The photons expelled from the spacecraft must, to some extent, be focused to provide thrust. If the Earth lies in the direction of the focused beam the lower limit in (10) might be reduced. In the absence of any knowledge of interstellar rockets (alien or otherwise) it is difficult to determine how large this effect might be. We can only note that in the 'high thrust' design of Morgan (1982) the flux in the reverse direction is enhanced by a factor ~ 75. This would enhance the flux seen by an observer in this direction by a factor ~ 8.5, since only $\sim 10\%$ of the photons are assumed to be so collimated.

5. Observational Considerations

5.1. Evolution

In this section we will consider other observable aspects of both kinds of antimatter propulsion spacecraft, and summarize the strategies for their detection. None of these other phenomena is so distinctive as the object's proper motion, which is why we have stressed the latter throughout.

The only constraint on the time evolution of the γ-ray emission is that it must last for a total time τ (Equation (8)). This value of τ may be split up in almost any conceivable way, over any total duration. It may be over-optimistic to expect any regularity in the spacing of engine firings. The resulting sources should, however, fall along a straight line if the proper motion is large enough (Section 2). Otherwise they will appear as successive outbursts of a single source.

5.2. Spectroscopy

The $p\bar{p}$ spacecraft will radiate primarily in the energy range 50–200 MeV (with a small 'tail' up to nearly 1 GeV), with peak emission around 100 MeV (Agnew *et al.*, 1960). If any photons from e^-e^+ annihilation escape (at most they will be about many as the high-energy photons) a broad ($\gtrsim$ 100 keV) line centered on 0.511 MeV will be observed. Note that all these energies will probably be highly Doppler-shifted. For the spacecraft in Table I, assumed to be following a tangential trajectory as seen from Earth at $0.9c$, the above energies will be red-shifted by over 40% by the transverse Doppler effect. From the e^-e^+ spacecraft only the 0.511 MeV line will be observed (together with such X-ray emission as may arise).

A problem with using their spectra to identify these spacecraft is that these features may mimic those of ordinary astronomical γ-ray sources. For example, the e^-e^+ spacecraft operating in a sparse short-pulsed mode would superficially resemble a series of γ-ray burst sources (in some of which the red-shifted 0.511 MeV annihilation line has apparently been seen: Mazets and Golenetskii, 1981. Sources showing emission above 1 MeV [Matz *et al.*, 1984] can probably be excluded.). The $p\bar{p}$ spacecraft would resemble sources such as Geminga (Bignami *et al.*, 1983) in which the energy emitted above 50 MeV exceeds that in the keV range by a factor $\sim 10^3$.

5.3. Search strategies

The most accurate possible measurement of γ-ray source positions is obviously a critical part of the strategy propounded here. A search with GRO can be supplemented by a search for linear relationships among γ-ray burst sources in catalogs such as the *KONUS Catalog* (Mazets *et al.*, 1981, in three parts) or that compiled by Baity *et al.* (1984), since, as noted above, such sources might be mimicked by e^-e^+ annihilation spacecraft.

In addition, if a proper motion candidate is identified, extrapolation forward and backward along its path should indicate a number of stars which are potential points of origin or destinations. Despite the pessimistic view of Wilson (1984), these stars (particularly F, G, and K dwarfs) should be targets for a conventional radio search.

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