JBIS Journal of the British Interplanetary Society

INTERSTELLAR STUDIES

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'OL. 43 No 12 DECEMBER 1990

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Journal of The British Interplanetary Society, Vol. 43, pp. 551-555,1990.

A SEARCH FOR LINEAR ALIGNMENTS OF GAMMA RAY BURST SOURCES

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Antimatter annihilation (electron-positron) spacecraft may mimic the behaviour of cosmic gamma ray burst sources. A search has been made for the linear alignments of bursts along the spacecraft trajectory which would result, using burst locations and spectra observed by the 1978-1980 Interplanetary Network of gamma ray detectors. No suspicious alignments have been found.

1. INTRODUCTION

This paper presents the results of what is believed to be the first observational search for extraterrestrial intelligence at gamma ray wavelengths. An earlier paper [1] suggested that occasional engine firings of antimatter annihilation (e^-e^+) spacecraft might mimic the behaviour of natural gamma ray burst sources (GRBs) and it was shown that the relativistic motion of the spacecraft led to the best observational methods of distinguishing them. Such motion gives rise to an apparent succession of GRBs along the line of the spacecraft trajectory, due to successive engine firings.

This suggestion is now followed up by searching for such linear alignments in a sample of well-observed GRBs. In section 2 the observed characteristics of GRBs are described and rigorous criteria developed for identifying alignments as spacecraft candidates. Reliance is placed, as far as possible, on very general features of e^-e^+ annihilation spacecraft, since no detailed designs for such vehicles exist. In section 3 the results of an automated search using these criteria are presented.

Gamma ray astronomy is a science in its infancy which suffers, in particular, from the poor angular and energy resolution of its detectors. The quantities involved are precisely those whose accuracy is most important for our search method. However, considerable improvements are likely in the near future, with the launch of NASA's Gamma Ray Observatory (GRO) anticipated in 1990. Hence, the results should be regarded mainly as a demonstration of the search method for fuller application in the GRO era. The quality of the current GRB data is discussed in section 3. Expectations for the future are set out in section 4 together with our conclusions.

2. SPACECRAFT IDENTIFICATION CRITERIA

2.1 Location of Events

The observed locations of GRBs are expressed as the angular coordinates of a spherical polar system (R.A. and Dec.), with no information available in the third (radial) coordinate. To define a line of GRBs in three dimensions, we begin by assuming that the acceleration of the spacecraft at each engine firing is so small as to be negligible. For relativistic spacecraft ($v \sim c$) this is reasonable given the short time-scales ~10 s characteristic of GRBs, since otherwise extreme accelerations $\geq 10^5\, g$ result, to the detriment of the structure and contents of the spacecraft.

Under this assumption the spacecraft velocity v is constant in both magnitude and direction. In effect, the spacecraft lies on a straight line in four dimensions. A minimum of three events is required to confirm the existence of a linear alignment, two of which define the line. If the spacecraft trajectory is sufficiently distant from the observer the line is seen projected on the celestial sphere as an arc of a great circle.

Given three GRBs with known R.A. and Dec. ($\alpha 1,\delta 1$), ($\alpha 2,\delta 2$) and ($\alpha 3,\delta 3$), the condition that they lie upon a great circle may be written [2]:

$$\cos(\delta 2)\cos(\delta 3)\sin(\delta 1)\sin(\alpha 2-\alpha 3)+\cos(\delta 3)\cos(\delta 1)\sin(\delta 2)\sin(\alpha 3-\alpha 1)+\cos(\delta 1)\cos(\delta 2)\sin(\delta 3)\sin(\alpha 1-\alpha 2)=0 \quad (1)$$

The angular separations d12 and d23 between the events may then be obtained from elementary formulae [2].

2.2 Event Times

The times at which GRBs occur are well-defined to within ~10 s, the typical duration of a burst. It is necessary that the times at which the events occur, rather than those at which they are observed, must be consistent with travel at constant velocity. No regularity in the timings of the engine firings is assumed.

In fig. 1 the three events are drawn in the plane containing the spacecraft trajectory and the observer O. Events A1, A2 and A3 occurring at times t1, t2 and t3 are detected at O at times T1, T2 and T3. The condition upon the event times is therefore:-

$$A1A2 = v(t2 - t1) = v\{T2 - OA2/c - (T1 - OA1/c)\}$$
$$A2A3 = v(t3 - t2) = v\{T3 - OA3/c - (T2 - OA2/c)\} \quad (2)$$

Owing to the lack of radial information, fig. 1 does not have an absolute length scale. Hence, v must be known, in order to provide a scale for lengths OA1, OA2 and OA3 in equation (2). In effect the condition upon the event times must be combined with a condition upon the spectra (from which v is obtained: see section 2.3).

Knowing v, then from elementary geometry (application of sine rule in triangles OA1A2 and OA2A3) OA2 and OA3 may be obtained in terms of A1A2 and A2A3. Substituting the expressions into (2), and eliminating A1A2 and A2A3 between the two equations, yields:

$$\frac{T3 - T2}{T2 - T1}\,\frac{\sin d12}{\sin d23}\quad\frac{\sin(a+d12+d23)}{\sin a}$$

$$= \frac{\sin d23 - v/c\,\{\sin(a+d12+d23) - \sin(a+d12)\}}{\sin d12 - v/c\,\{\sin(a+d12) - \sin a\}} \quad (3)$$

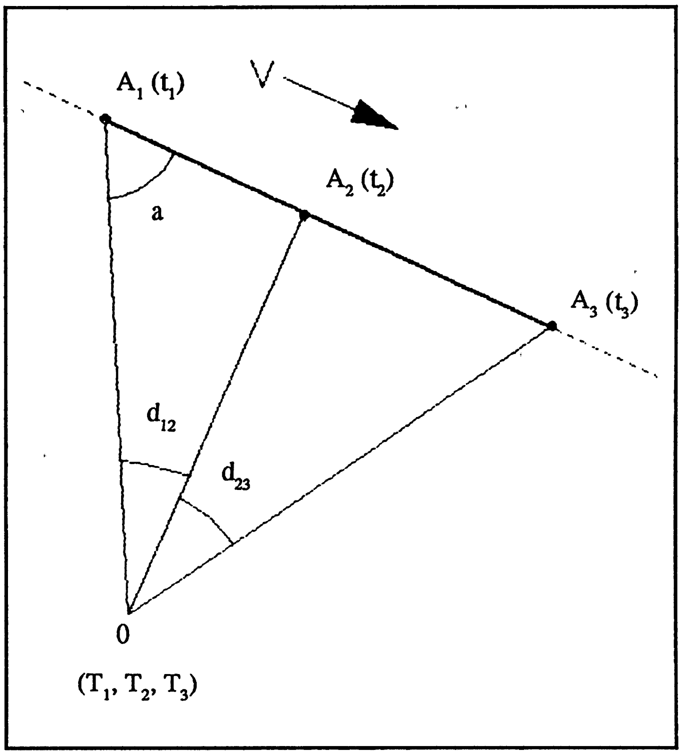

Fig. 1 An alignment of three GRBs A1, A2, A3 drawn in the plane containing the three bursts and the observer 0. The event times at each burst, and as seen by 0, are in parentheses.

If v is known this equation may be solved for a, the angle made by the trajectory at the first event (fig. 1), thus defining the line in three dimensions despite the lack of radial information.

2.3 Energy Spectrum

The annihilation of a large mass of positrons in an e^-e^+ spacecraft engine would be expected to produce primary gamma-ray emission in the well-known line at 0.511 MeV and in the positronium continuum below this energy. Another source of continuum at lower energies might be re-processing into X-rays of the gamma rays in the spacecraft's structural material (if any). If the temperature of annihilation is comparable to nuclear fusion temperatures, the line will be broadened to ~100 keV and a further continuum contribution will arise from thermal emission (bremsstrahlung or other) at energies up to ~1 MeV. The overall picture is of a steeply-sloping continuum from the X-ray absorption regime ~10 keV to ~1 MeV with a single emission line superimposed. The line will be Doppler-shifted by the spacecraft's rapid motion. The relative strengths of the line and the continuum cannot be estimated without knowing details of the spacecraft design.

The spectra of GRBs are observed to show steeply sloping continua between ~10 keV and 1 MeV, or in some cases higher. The continua are compatible with thermal bremsstrahlung emission at ~3×10^8 K, or with a thermal synchrotron process at somewhat lower temperatures if strong magnetic fields are present [3]. Many spectra also show single emission features at energies of a few hundred keV which have been interpreted as Doppler-shifted 0.511 MeV annihilation lines [4]. The line widths range from the energy resolution limit, which in this region is a few tens of keV, up to ~250 keV. The Doppler shifts are generally red but, unfortunately, the signal-to-noise ratios are so poor that the reality of the lines is debatable [5]. This problem increases with energy so the existence of blue-shifted lines would be very difficult to establish. It is assumed here that the lines are real. If so, the similarity between GRB spectra and those expected from e^-e^+ spacecraft is remarkable [1].

If the spectrum of the event A1 in fig. 1 exhibits an annihilation line at energy E_1, the expected Doppler shift is [6]:

$$E_1/E' = E_1/0.511 = (1 - v^2/c^2)^{1/2} / (1 - v/c \cos a) \qquad (4)$$

whence

$$v/c = \frac{\{1 - (E_1/E')^2 \sin^2 a\}^{1/2} + (E_1/E')^2 \cos a}{1 + (E_1/E')^2 \cos^2 a} \qquad (5)$$

Similar formulae for events A2 and A3 arise by modifying a. It will be seen that if any one of the three GRB spectra contains an emission line, equations (3) and (5) may be regarded as simultaneous equations in a and v, by whose solution the spacecraft trajectory is completely determined. Additional information from the other spectra is then necessary to confirm the alignment.

It should be noted that the well-known relativistic transverse Doppler effect ($a = \pi/2$ in equation [4]) ensures that, at its closest approach to the observer, the spacecraft spectrum is red-shifted. Since it is most likely to be detected in this part of its trajectory, this is consistent with the fact noted above that GRB annihilation lines are generally red-shifted.

2.4 Time History and Energy Flux

The evolution of the spectra and total energies during the burst is well known for many GRBs. Unfortunately a comparison with what is expected from e^-e^+ spacecraft is difficult, because the most basic details about the spacecraft are not known. For example, the energy release from the annihilation can be obtained from the measured energy flux if the trajectory is known. However, to evaluate the plausibility of this number in terms of fuel requirements and the acceleration that would result from it, knowledge of the spacecrafts's mass is needed, and this is utterly unknown. Without such information about the spacecraft, no attempt will be made to set criteria involving these two observables.

2.5 Summary of Spacecraft Identification Criteria

The following criteria are arrived at for identification of a linear alignment of GRBs. In our search method, they are applied successively to a sample of observed GRBs:

(1) Groups of at least three GRBs which lie on a great circle according to equation (1) are identified.
(2) At least one of the GRB spectra must show an annihilation line, from whose Doppler shift the possible three-dimensional trajectory is determined by solving equations (3) and (5) simultaneously for a and v.
(3) A spacecraft candidate is identified if spectra are available for the other GRBs in the alignment and if these spectra show annihilation lines at the energies given for these values of a and v by equation (4).

3. SEARCH METHOD AND RESULTS

3.1 The 1978-1980 Interplanetary Network Data

Due to the inherent poor resolution of gamma ray detectors, the locations of most GRBs are very poorly known. The best method of locating a GRB is to compare the arrival time of the burst at several widely-spaced detectors, usually those placed on board interplanetary spacecraft [7]. Conditions for this method were exceptionally favourable during the period 1978-1980, when data were obtained from several detectors in near-Earth and Lagrange-point orbits, from the Pioneer Venus Orbiter at Venus, and from Venera 11 and 12 in heliocentric orbits.

The data used in the present search were obtained from this 1978-1980 Interplanetary Network. A catalogue of the GRBs detected was compiled by Atteia *et al* [8], in which locations were given for 69 events with varying levels of accuracy. For 54 of these events unique locations were assigned. For the remainder, either of two separate locations was possible. The uncertainties in the positions are characteristically ~10 deg^2; very frequently the error boxes are arcuate (small-circle arcs of several degrees length, with negligible breadth). Several other GRBs were detected only by the KONUS experiment on the Venera spacecraft whose detectors had a fairly good angular response [9]. Eight such events having error box areas < 75 deg^2 were also included in the search.

Spectra were obtained from nearly all these GRBs by the KONUS experiment [10]. The energy range was from ~20 keV to an upper limit which, depending on the continuum slope, might be up to ~1 MeV. Of these spectra, 12 exhibited an emission feature which could be regarded as a Doppler-shifted annihilation line, 16 definitely showed no such line up to 1 MeV, and the remaining spectra were not of sufficient extent to form a judgement, i.e. without knowing in advance where the line ought to be. The GRB observed times were taken to be the Earth-centre crossing times computed by ref. [8], which are accurate to 1 s.

3.2 Search Method

The GRB locations described above were searched in groups of three for great-circle alignments, as defined by equation (1), which were monotonic in time and of total extent < 180°. Both locations were searched in cases where two alternative positions were possible; alignments containing the two were, of course, excluded. A maximum value of the function on the left-hand side of equation (1) was selected, taking into account typical error box dimensions, below which the three points were selected as an alignment candidate. A value of 0.125 was found to be suitable for the characteristic several-degree arc uncertainties.

Only those alignment candidates were retained in which at least two GRBs exhibited a possible annihilation line. From the line energy in the earliest-time spectrum and from the alignment geometry, a numerical solution of equations (3) and (5) was performed simultaneously for v and a. The trajectory then defined, a search was performed along it for further (fourth, fifth and higher) members. The annihilation-line Doppler shifts expected in the two remaining GRBs in the original alignment were calculated on the basis of these values of v and a, and the resulting line positions were compared by eye with the KONUS spectra.

3.3. Results

Out of more than 6000 alignments found according to equation (1), only 134 possessing adequate annihilation-line data were retained whose trajectories were calculated. One alignment of four GRBs was found. Every one of these alignments was excluded as a spacecraft candidate upon comparison of the predicted and observed annihilation-line energies.

A typical alignment of three GRBs is illustrated in fig. 2, where the gnomonic projection used maps the great circle as the straight line linking the three events. The observed properties of the GRBs are listed in Table 1. Note the very large arcuate error box of the 18 September 1978 event, which detracts considerably from the plausibility of the alignment. From the observed positions and times and the 18 September 1978 red-shift a velocity of 0.915 c was inferred and the spacecraft trajectory of fig. 3 was constructed, using equations (3) and (5). The event times at the spacecraft candidate and at the Earth (in parentheses in fig. 3) are expressed in days relative to the time of the first GRB detection at Earth, $19^h49.6^m$ UT on 18 September 1978. It can be seen that the spacecraft candidate passed closest to Earth at a distance of 0.45 light years on 29 June 1978.

The KONUS spectra of the three GRBs are shown in fig. 4. An arrow at left indicates the proposed red-shifted 0.511 MeV annihilation line in the 18 September 1978 spectrum. Note the weakness of the feature compared to the noise, which again detracts from its plausibility. The uncertainty in its energy is ~50 keV but it can be shown that the trajectory calculation is rather insensitive to errors in v from Doppler-shift uncertainties, burst position uncertainties being much more important. In the

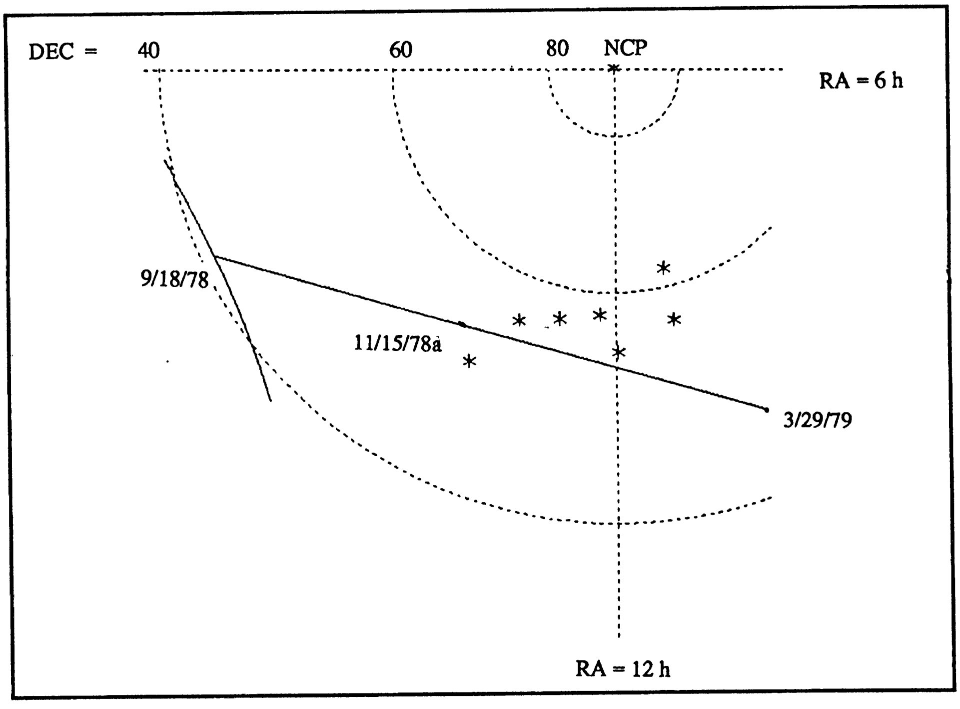

Fig. 2 A typical alignment discovered during the search, drawn against the celestial sphere in gnomonic projection. The three GRBs are identified by date (and order a, b... if necessary) as in refs. [8, 10], and drawn with three error boxes.

TABLE 1: *Observational data for a typical alignment*

Event I.D.	Time UT	Location[1] R.A. Dec.	Error Box[1] R.A. Dec.	e^-e^+ Line Energy, keV
9/18/78	$19^h 49.6^m$	241.0 +40.5	258.8 +39.6 226.3 +38.4	400±50
11/15/78a	$21^h 7.4^m$	210.8 +52.2	211.1 +52.0 211.7 +52.3 210.5 +52.3 210.0 +52.0	[2]
3/29/79	$22^h 21.9^m$	157.0 +45.9	[3]	[2]

[1] All R.A. and Dec. in degrees.
[2] Annihilation line not seen in these spectra.
[3] Error box for 29 March 1979 burst is negligible.

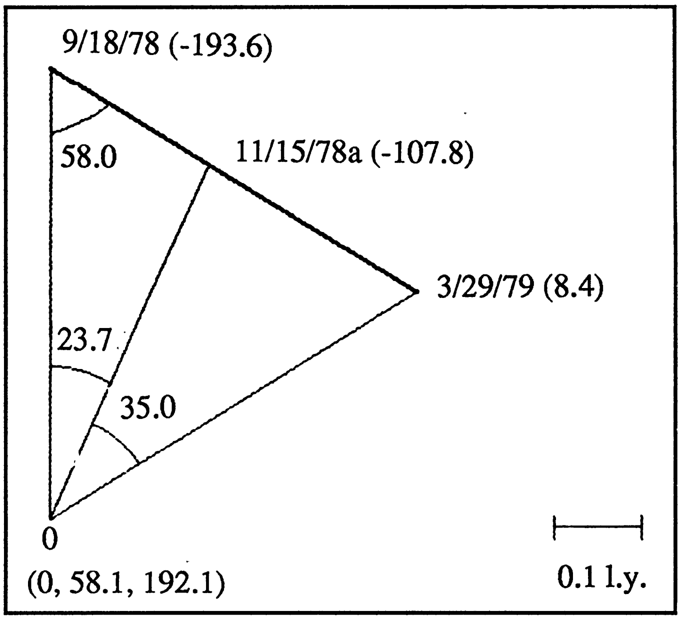

Fig. 3 Trajectory in space of the spacecraft candidate in fig. 2, drawn in the plane containing the Earth and the three GRBs. Length scale is at lower right. Event times in days at each burst and at Earth, relative to the detection of the 18 September 1978 burst, are given in parentheses. All angles are in degrees.

two other spectra in fig. 3, arrows indicate the expected energies of the 0.511 MeV line if it is to be consistent with the 18 September 1978 line. The fact that no features are visible at these energies in either spectrum causes the rejection of this alignment as a spacecraft candidate.

4. DISCUSSION

4.1 Reliability of Search Method

The large error boxes associated with many of the GRBs in this sample imply that alignments in which the events are closer together than several degrees cannot be trusted. Given velocities v~c, this, in turn, implies that spacecraft cannot be identified at distances from Earth greater than a few light years. It is improbable, in view of the negative results from radio SETI searches of nearby stars [11], that an alien spacecraft would be found within the small volume ~1 pc^3 of space thus searched.

Another consequence of the large error boxes is that the alignment criterion limit in equation (1) must be set high, thereby enormously multiplying the number of alignments due to pure chance which will be found by that criterion. In fact, the quality of the Interplanetary Network GRB locations is so poor that it is questionable whether any alignment detected in this data set can be credible.

Conversely, the search method employed here has been shown to be acceptably rigorous by the very fact that it has not generated spurious spacecraft candidates in a situation where none could be expected. Specifically, the use of annihilation-line Doppler-shift criteria is found to be a satisfactory corrective for the problems arising from the location uncertainties, thus creating confidence that the method can usefully be applied to the higher-quality GRB data which should become available in the 1990s (see section 4.3).

4.2 Extensions of Search Method

The fact that the search method generates a well-defined three-dimensional spacecraft trajectory makes it very powerful if a good spacecraft candidate should be detected, since extrapolation forwards and backwards along the trajectory is then possible. This capability opens up many possibilities for confirming or refuting the identification. Obviously, the locations and times of future GRBs can be predicted to the extent that they must lie on the trajectory. The starting points and destinations of the flight might also be identified, to be targeted for radio and other studies. The antapex and apex of the trajectory (the points 90° from the point of closest approach), which are the obvious places to begin such a search, are well-defined. For example, if the alignment illustrated in figs. 2 and 3 were a true spacecraft candidate, it would be suggestive (given the trajectory's close approach to Earth) that the trajectory extrapolated forward passes about 3° from the nearby star Procyon, being then ~5° from its apex. It is even possible to estimate the time of arrival at this destination.

The Doppler-shifts of annihilation lines in future GRBs along the trajectory can also be predicted. In fact, the interesting possibility arises that, if e^+e^- spacecraft are responsible for some GRBs, then blue-shifted annihilation lines are possible (although red-shifts are more likely: see section 2.3). Unlike red-shifts, which in GRBs are generally attributed to strong gravitational fields, blue-shifts would be extremely difficult to explain other than as a velocity effect. Note, however, that annihilation in flight of naturally relativistic electrons and positrons, e.g. in cosmic rays, might produce a blue-shifted line under restricted physical conditions.

It is also noted in passing that, due to the lack of identification of GRBs at any lower wavelength (which, except possibly for artificial radio emission, is not unexpected in a spacecraft model), their theoretical interpretation is a notoriously perplexing problem (see e.g. ref [12]). Those cases where annihilation lines are seen have been especially difficult to model. A new line of investigation may be opened up if models in which some GRBs are artifacts are admitted.

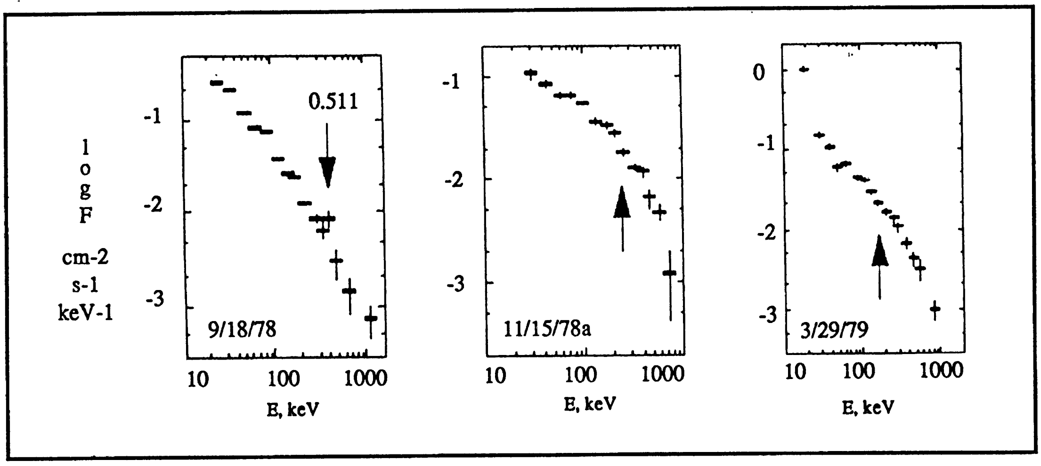

Fig. 4 KONUS energy spectra of the three bursts in the alignment of figs. 2 and 3. Arrow at left shows possible 0.511 MeV e^-e^+ annihilation line. Arrows in center and right panels show predicted energies of the annihilation line in these spectra.

Methods of identifying antimatter spacecraft propelled by proton-antiproton annihilation are briefly discussed in ref. [1].

4.3 Future Prospects

The key to improving the application of this method is obviously a major improvement in the accuracy of GRB locations. The prospects for a renewal of the Interplanetary Network are unclear, due to uncertainties in launch schedules and in the lifetimes of existing instruments. Improvements, instead, are expected in the angular resolutions of individual detectors, starting with a dedicated GRB experiment to be launched on GRO in March 1990.

The Burst And Transient Source Experiment (BATSE) will detect GRBs whose energy output is predominantly between 30 and 600 keV, with spectra of the stronger sources taken up to 20 MeV. The detector angular resolution ranges from ~10° for the weakest GRBs down to ~0.5° for the strongest [13]. The spectral energy resolution will be about the same as that of the KONUS experiment (fig. 4) for the weaker bursts, and about 2-3 times better than KONUS for the stronger bursts. The lifetime of GRO is expected to be from 2 to 10 years (depending on the availability of in-flight servicing), during which time BATSE ought to detect several thousand events. The number which will be usable by this search method will depend on the frequency of detection of annihilation lines (if any) in the BATSE spectra. However, the improvement in accuracy of burst locations is highly promising for the method.

If sufficient GRB location accuracies can be achieved, further improvements in the prospects for a spacecraft search will come mainly from the increased sensitivity of future detectors. The BATSE large-area detector is already an order of magnitude more sensitive than the KONUS experiment, the main limiting factor, from this point of view, in the Interplanetary Network data. For a given size of spacecraft, increases in detector sensitivity translate into larger distances from the Earth out to which the search can be carried, if angular resolution is no longer the limiting factor.

5. CONCLUSIONS

The following conclusions may be drawn.

(1) No e^-e^+ - annihilation spacecraft can be identified among the GRBs observed by the 1978-1980 Interplanetary Network of gamma-ray telescopes.

(2) The main limiting factor on our search method is the angular resolution attainable by current gamma-ray telescopes and arrival-time techniques.

(3) The search method described may be applied with confidence when better angular resolutions become available in the GRO era.

ACKNOWLEDGEMENTS

I am grateful to Dr. J.-L. Atteia for communicating his results in advance of publication, and to Dr. R.L. Forward and Dr. A.C. Edwards for advice and encouragement.

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