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A DISTANCE LIMIT FOR A CLASS OF MODEL GAMMA-RAY BURST SOURCES

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Abstract Gamma ray burst sources are presumably not larger than 10^9 cm as inferred from observed flux variations. If they are homogeneous and isotropically radiating, then from photon density considerations, they would have to be optically thick due to gamma-gamma pair production when assumed to be too far away. Deviations of observed photon spectra from an exponential shape around 1 MeV lead to an upper limit of the possible distance of such sources of only 2 kpc from the sun. Thus the sources must be galactic unless the radiation is highly beamed or emerges from a relativistically moving shell. This conclusion depends only on observed parameters. The possible presence of particles and fields in the sources would require them to be even closer.

The observed time structures of gamma-ray bursts of the type reported by *Klebesadel et al.* [1] place an upper limit $\ell \approx 10^9$ cm on the typical size of the burst source regions [2]. If the sources were too far away and isotropically radiating then the observations would require such a high density of photons that the sources would be optically thick in the MeV region simply due to gamma-gamma pair production. These considerations do not apply directly to highly beamed sources or relativistically expanding sources. In the following it will be pointed out that MeV photons have actually been observed in bursts, and that this means that non-relativistic sources cannot be further away than a few kpc from the sun and therefore must be galactic.

Some of the presently available spectral burst data [3-7,29] show a significant flux of photons in the > 1 MeV range [3-5,29]. The 27 April 1972, event observed by Apollo 16 [3] shows at higher energies a power law spectrum with a possible line feature around 4 MeV. However, power law spectra and lines cannot escape with significant intensity from homogeneous optically thick sources, and if the lines were generated in different spatial regions that are optically thin it would seem to be difficult to get the energy into these regions to excite MeV lines and nothing else. Another possibility would be to generate the burst in a thin shell surrounding the volume of radius ℓ. But that does not significantly decrease the self-absorption of the source as will be shown later.

In case of rapidly varying thermal radiation from an optically thick source it is not easy to construct a spectrum that is a power law at high energies when integrated over the burst duration. A cooling blackbody can account for some lower energy features of the burst spectrum [8], but not for the high energy tail.

For most events there is insufficient information available on the time structure of the burst around 1 MeV. However, the 18 December, 1972, event - although it was not observed at 1 MeV - showed no rapid spectral changes on the time scale of the fast sub-bursts [7], and a generally increasing hardness near the beginning of the burst. These data hint that the high energy fast time structure is not significantly different from the lower energy time structure.

The significance of photon-photon pair production in astrophysical situations has been investigated for a variety of cases. *Nikishov* [9], and *Fazio* and *Stecker* [10] considered the absorption of very high energy photons by thermal photons in intergalactic space. *Jelley* [11] investigated that same mechanism for quasars and other radio sources. *McBreen* [12], and *Stecker* and *Tsuruta* [13] applied these considerations to the Crab pulsar NP0532, and *Rengarajan* [14] considered the escape of gamma rays from hot neutron star surfaces. In a more general assessment *Herterich* [15] showed that intense X-ray sources are optically thick for gamma rays above a few MeV and therefore cannot be high energy gamma ray sources.

To estimate the optical depth of a homogeneous, isotropic radiation field we will use the formulae as used earlier by *Nikishov* [9], *Jauch* and *Rohrlich* [17], and *Gould* and *Schréder* [16]. For simplicity we assume that all photon-photon encounters take place at $\Theta = 90^{\circ}$ between the momentum vectors of two interacting photons. The threshold energy ε_{th} of an ambient photon for photon-photon pair production, interacting with a test photon of energy E, is

$$\varepsilon_{th} = (2m^2c^4) / E\,(1-\cos\Theta). \qquad (1)$$

Here mc^2 is the electron rest energy. The cross section $\sigma_{\gamma\gamma}$ has a maximum of 1.7×10^{-25} cm^2 at $\varepsilon_o = 2\,\varepsilon_{th}$.

For a typical source radius ℓ and ambient photon density n cm^{-3}, the optical depth for the test photon is typically

$$\tau(E) = \ell \int_{\varepsilon_{th}}^{\infty} n(\varepsilon)\, \sigma_{\gamma\gamma}(E,\varepsilon)\, d\varepsilon, \qquad (2)$$

With the observed photon number flux $F(\varepsilon)$ cm^{-2} s^{-1} keV^{-1} the spatial density of photons on the surface of the source is $n = (F/c)(D^2/\ell^2)$ where D is the distance of the source; hence

$$D(E) = \left(\frac{\tau \cdot \ell \cdot c}{\int_{\varepsilon_{th}}^{\infty} F(\varepsilon)\sigma(E,\varepsilon)\, d\varepsilon} \right)^{1/2} \qquad (3)$$

For integration we make two alternate assumptions for the spectral shape of the flux $F(\varepsilon)$ cm^{-2} s^{-1} keV^{-1}. We consider (a) a composite spectrum [4]

$$\frac{F^{(a)}\,\mathrm{cm^{-2}sec^{-1}keV^{-1}}}{\mathrm{erg/cm^2\ sec}} = \begin{cases} 1.6 \times 10^4 \exp\left(-\frac{\varepsilon}{150\,\mathrm{keV}}\right) & \varepsilon \leq 375 \text{ keV} \\ 3.9 \times 10^9 \left(\frac{\varepsilon}{\mathrm{keV}}\right)^{-2.5} & \varepsilon > 375 \text{ keV} \end{cases}$$

and (b) for comparison we consider a pure power law

$$\frac{F^{(b)}\,\mathrm{cm^{-2}sec^{-1}keV^{-1}}}{\mathrm{erg/cm^2\ sec}} = 1.9 \times 10^8 \left(\frac{\varepsilon}{\mathrm{keV}}\right)^{-2}$$

This is the photon number flux normalized to a burst of integrated energy flux of 1 erg/cm^{2}sec. For normalization of case (b) we have assumed that 70 % of the usually quoted energy of the burst is found between 100 keV and 1000 keV.

As an example we take a typical burst of size 10^{-4}erg cm^{-2}. The actual energy flux per second of such a burst is around 3×10^{-5}erg cm^{-2}s^{-1} with wide variations. We assume now that the optical depth of the source region should be $\tau < 1$ in order to assure the escape of the test photon. With this we arrive at Figure 1. Since a fair number of events have been detected near 1 MeV[3-5,29], and all show deviations from an exponential spectrum, we take the $\tau = 1$ distance derived for 1 MeV for the upper limit of the distance to a 10^{-4}ergs/cm^2 homogeneous isotropic burst source, which is $D \approx 2$ kpc according to Figure 1. Thus this type of burst source must be galactic. The photon number flux fluctuates greatly during the burst, and the actual momentary fluxes are often significantly greater than the average fluxes. So our upper limit should be a rather generous one.

This distance limit was estimated for $\ell = 10^9$cm sources which are isotropically radiating with initial photon density constant throughout the source volume and the same as on its surface. If the radiation were to emerge only from a surface around the source, but each surface element were radiating isotropically, then near the source the photon density would still be quite high, but the average angle of encounter would be less than 90°. A similar situation was considered earlier [18], and for our case we find that the $\tau = 1$ distance would be insignificantly larger than our upper limit. Also, if the high energy radiation of the 27 April, 1972 event were a 4.4 MeV Carbon line feature with a typical time scale of about 5 seconds and intensity 10^{-1}sec^{-1}cm^{-2}, then the typical source radius would be about 10^{11} cm, and the resulting $\tau = 1$ distance would be about 3×10^5 pc. Thus even this very extreme assumption would keep the source well within the local group of galaxies.

Within 2 kpc of the sun there is about 1 % of the galactic mass; this holds for either all matter [19] or the extreme Population I as represented by the Hydrogen disk [20]. If the bursts come from objects distributed throughout our galaxy similar to either one of the two classes of objects then bursts of size 10^{-4}erg cm^{-2} come from only about 1/100 of the galaxy. Assuming the widely used standard candle hypothesis where the burst size is inversely proportional to the square of the source distance, the frequency of bursts of size $\geq$ S is at the same time a lower limit to the frequency of occurrences of bursts at distance $\leq$ D(S). Since the frequency of detections of 10^{-4} erg cm^{-2} bursts is about 3 y^{-1} [21,22] the upper limit to the distance leads to an upper limit of the average intrinsic luminosity of $\approx 5 \times 10^{40}$ erg and to a lower limit of about 300 burst occurrences per year throughout our galaxy.

This means that unless very special radiation mechanisms are at work occurrences that are unique in the history of an individual star cannot account for the majority of the bursts that are being detected. The rate of star formation in our galaxy is at present about two to three solar masses per year [23] and supposedly has been constant for the last few billion years. We assume for the sake of this argument that this means two to three stars per year. It is difficult to see how the rate of irreversible star transformations could be two orders of magnitude higher than this rate at the present epoch. Nova explosions also have been suggested as gamma ray burst sources. The rate of optical novae per year has been estimated to be about 30 to 50 in our galaxy [24,25], and 25 to 30 in M31 [26,27]. These numbers would be, considering the usual uncertainty of numbers in astrophysics, marginally compatible with our number of burst occurrences. However, considering the high degree if isotropy of the detected burst directions [21,28] we feel we can also exclude novae as the major contributors to gamma ray bursts. Therefore, we suggest tentatively that the gamma ray bursts that have been detected are galactic, but are in the majority of the cases not connected with unique irreversible star transformations, and also it is unlikely that they are connected with galactic novae.

In the case of beamed sources the threshold energy (1) depends on the opening half angle $\Gamma/2$ of the beam. Using the same arguments as *Stecker* and *Tsuruta (1972)* [13] we assume $\Theta \approx 2^{1/2}\ \Gamma/2$. Assuming that 5 MeV photons have been observed [3,5] we set $\varepsilon_{th} \approx 2.5$ MeV and from this with (1) we derive $\Gamma/2 \approx 12^{\circ}$. With (3) we find that such a source should be optically thick ($\tau = 1$) at 5 MeV if placed further than 6 kpc from the sun. The galactic fraction of matter within this distance is about 1/10 of the total, and the solid angle covered by the $\Gamma/2 = 12^{\circ}$ bursts is 1/8 sr, so that in the same way as above we arrive at a minimum number of burst occurrences throughout the galaxy of $8 \times 4\pi \times 10 \times 3 \approx 3000\ y^{-1}$. Hypothetical beams narrower than 12° cannot at present be assessed in this way, because the energy where absorption can become important ($\lesssim 2\ \varepsilon_{th}$) is presently not covered by observations. Thus for not too narrow beams the conclusions are essentially the same as above.

We wish to emphasize here that the conclusions reached depend entirely on observed parameters. No specific assumption had to be made about particles or fields within the sources. Generally, particles or fields can also serve as absorbing agents so that their presence can only increase the optical depth of the source and therefore put even more severe constraints on the distance of the sources.

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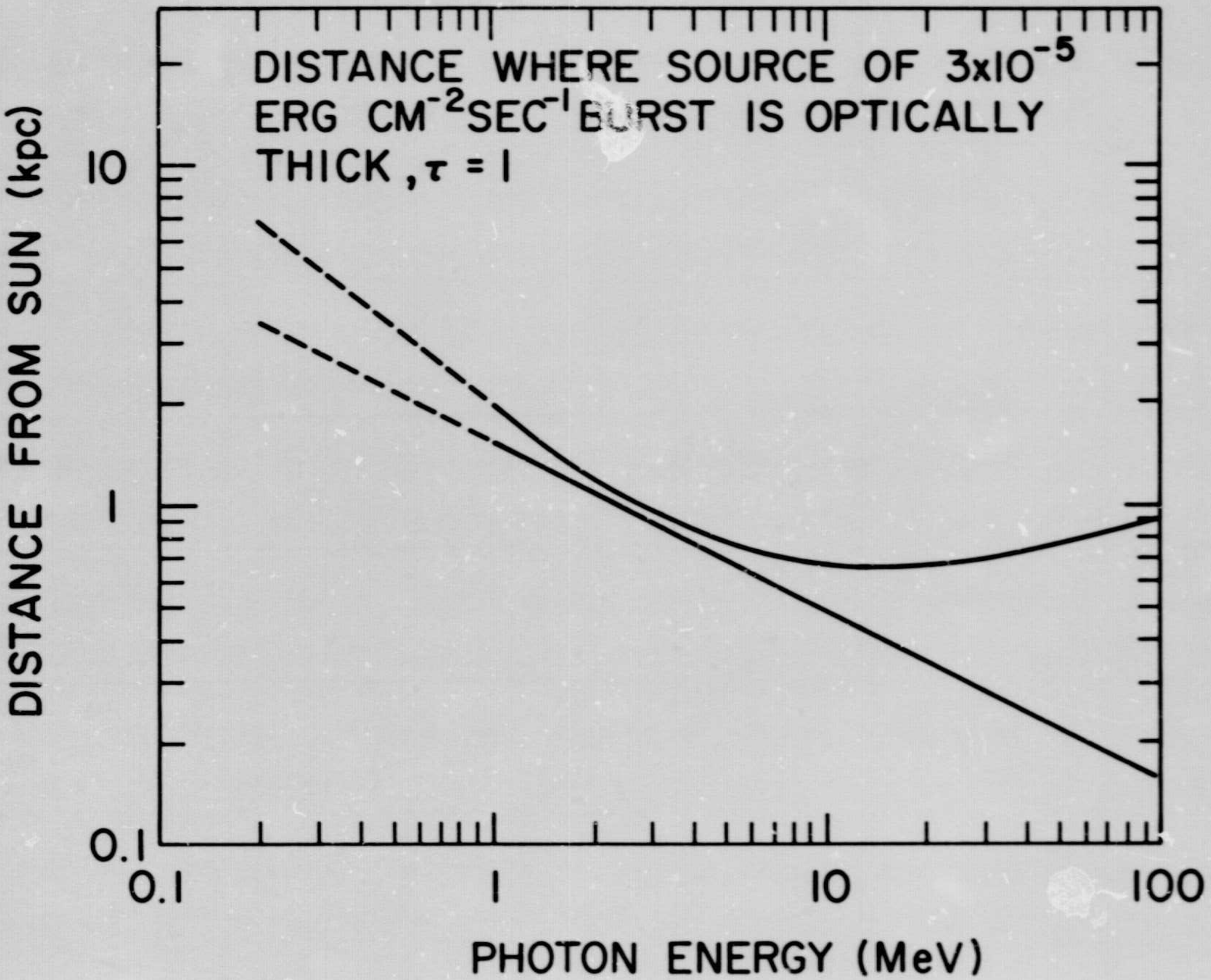
Figure Caption:

Homogeneous isotropically radiating burst sources are optically thick at the abscissa energy if assumed to be further away from the sun than indicated on the ordinate. The two photon number spectra of bursts (upper curve for the composite spectrum) have been assumed without cutoffs. For details see text.


DISTANCE WHERE SOURCE OF 3x10^-5 ERG CM^-2 SEC^-1 BURST IS OPTICALLY THICK, τ = 1
DISTANCE FROM SUN (kpc)
10
1
0.1
0.1
1
10
100
PHOTON ENERGY (MeV)