

## ANNIHILATION RADIATION IN COSMIC GAMMA-RAY BURSTS

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The pair annihilation radiation in gamma-ray bursts is seen as broad lines with extended hard wings. This radiation is suggested to escape in a collimated beam from magnetic polar regions of neutron stars.

Cosmic gamma-ray bursts are widely believed to be generated on strongly magnetized neutron stars. The strongest support for this hypothesis comes from the observation in the gamma-ray burst spectra of absorption and emission features which are supposed to be cyclotron and gravitationally redshifted annihilation lines, respectively (Mazets et al., 1981, 1982; Teegarden and Cline, 1980; Hueter and Gruber, 1982). However the origin and emission mechanism of gamma-ray bursts remain unclear (Lamb, 1984; Liang, 1984; Woosley, 1984). This emphasizes the need in a comprehensive study of the spectral behavior of bursts.

The Konus experiment on the Venera 11 to 14 spacecraft carried out in 1978 through 1983 has revealed over 350 gamma-ray bursts. Several tens of events exhibit in their spectra emission features. In many cases the statistical accuracy of measurements was high enough to provide more accurate information on the spectral shape of these features.

The new data show that the emission features represent very broad asymmetric lines with extended hard wings. This means that the gamma-ray bursts under study are made up essentially of two radiation components. The first (softer) component is characterized by an exponential falloff with increasing photon energy. The spectrum drops steeply below 1 MeV. This component is similar to the continuum spectra of the bursts without emission features.

The second (harder) component exhibits a low-energy cutoff below  $\sim 300$  keV. The position of the spectral

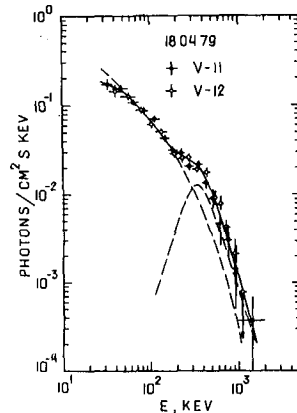


Fig.1

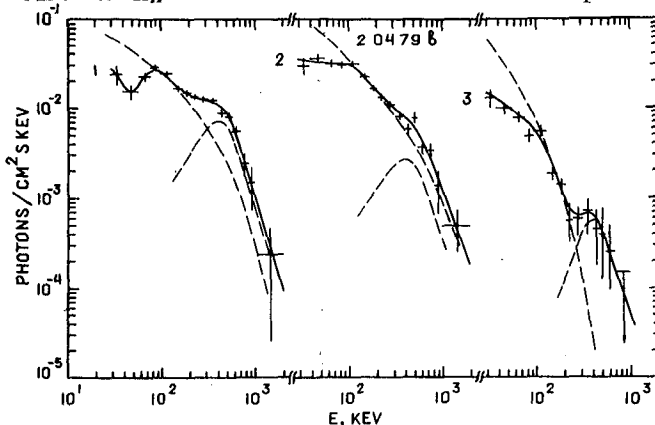


Fig.2

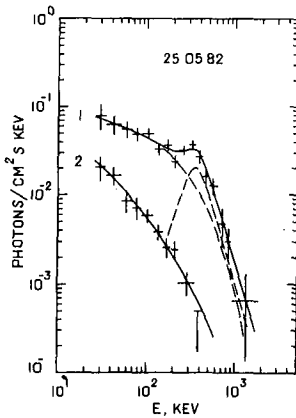


Fig.3

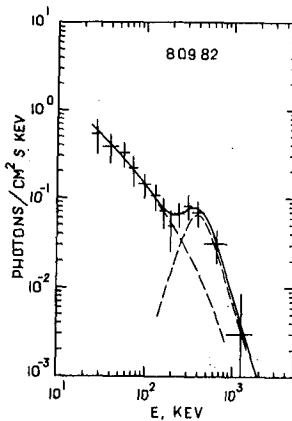


Fig.4

maximum varies from  $\sim 350$  to 450 keV for different events. This narrow region corresponds to the gravitational redshift of the pair annihilation radiation produced near the surface of a neutron star. The hard wing of the feature extends toward high energies by approximately a power law with a slope of  $-2.5$  to  $-3.5$ . It is highly probable that the hard tails in the gamma-ray burst

spectra revealed in the SMM data (Rieger et al., 1982) originate in such features (Mazets et al., 1983).

In the present report we are going to submit only a few observations of annihilation features as well as some considerations concerning their possible interpretation. The results obtained will be treated in more detail elsewhere.

We have fitted the shape of the photon energy spectrum having an emission feature with a sum

$$dN/dE = AE^{-\gamma} \exp(-E/kT) + B \frac{E^{\alpha}}{E^{\beta} + (kmc^2)^{\beta}} \quad (1).$$

The first term of this expression describes satisfactorily the spectrum of a continuum without the absorption and emission features (Mazets et al., 1982). The second term is a simple model for the hard radiation component representing a broad line with an extended hard wing. This function grows as  $E^{-\alpha}$ , passes through a maximum at  $E_{\max} = [\alpha/(\beta-\alpha)]^{1/\beta} kmc^2$ , and falls off after this as  $E^{-(\beta-\alpha)}$ . The parameter  $k$  permits shifting the distribution along the energy axis.  $A$  and  $B$  are dimensional normalization factors.

Consider examples of such representation of the gamma-ray burst spectra with clearly pronounced features. Fig.1 shows a photon spectrum of the 18 April 1979 event. The experimental points exhibit a complete agreement between the measurements performed on the two spacecraft. The solid line at energies above 50 keV corresponds to relationship (1). The two radiation components are shown separately by dashed lines. The parameter adjustment was performed by minimizing the sum  $\sum_j (N_{j\text{obs}} - N_{jc})^2 / \sigma^2(N_{j\text{obs}})$  where  $N_{j\text{obs}}$  is the experimental value of the photon flux in channel  $j$  of the spectrum, and  $N_{jc}$  is the corresponding value calculated by Eq.(1). The  $\chi^2$  test ( $\chi^2_{q-p} = 23$  for the number of the degrees of freedom  $q-p=24$ ) showed this approximation to be satisfactory.

Fig.2 displays three spectra of the 2 April 1979 event measured consecutively with a 4 s accumulation time. In addition to a strong annihilation component, the spectra contain also an intense cyclotron feature. Both the continuum and the features exhibit a strong and independent variability. The hard component in the energy spectra can evolve on a very fast time scale. Fig.3 shows two spectra of the 25 May 1982 gamma-ray burst. The strong annihilation line is seen only in the first spectrum measured with an accumulation time of 1 s.

It is remarkable that the annihilation component is present also in some very short gamma-ray bursts. Fig.4 presents a spectrum of the 8 September 1982 event which lasted only for 100 ms.

The above examples represent only a small fraction of the available data on the bursts exhibiting this pattern of spectral behavior.

The spectral range of our measurements extends only as far as 2 MeV. Therefore we cannot provide direct evidence which would show that the hard wing can extend up to several MeV and even higher. There is, however, a remarkable observation supporting our suggestion. Fig.5 presents a spectrum of the 25 March 1978 event measured on HEAO-1 up to about 10 MeV (Hueter, 1984). One can see here both types of spectral features. Our approximation of this spectrum with the two-component model yields a result which does not differ from the other cases considered.

In conclusion consider a possible explanation for such a spectral behavior of the annihilation radiation from a pair plasma assuming its temperature to vary within a fairly broad range,  $kT$  0.1-5 MeV. In Fig.6 constructed from the data of Ramaty and Mészáros (1981) the solid lines correspond to annihilation spectra for a plasma with the temperature varying from  $3 \times 10^8$  to  $3 \times 10^{10}$  K. The dashed line is a result of superposition of these spectra. While being schematic, this result nevertheless exemplifies clearly the possibility of formation of an annihilation spectrum with a maximum around  $mc^2$  and a hard power-law wing. This situation can apparently become realized in a plasma with a spatially nonuniform and/or rapidly varying temperature.

As follows from the data obtained, the line energy flux  $S_1$  is comparable with the continuum energy flux  $S_c$  and even may exceed it, i.e.  $S_1/S_c = 1$  to 4.

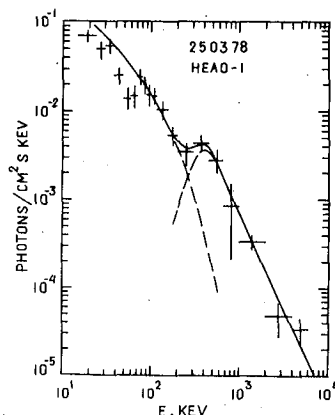


Fig.5

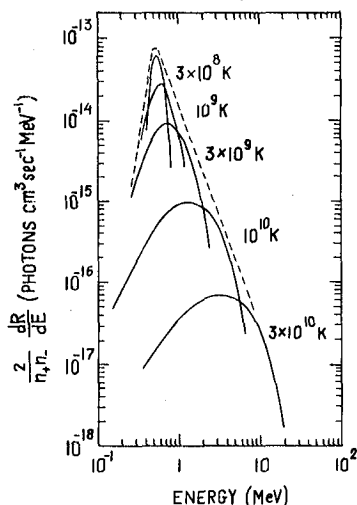


Fig.6

We believe that such a ratio can be accounted for by different directional patterns of these two components. The location and temperature of the regions responsible for the line and continuum radiation are apparently different. The magnetosphere of a neutron star is opaque to hard radiation. Therefore the pairs formed in the  $(\gamma\gamma)$  and  $(\gamma\beta)$  processes above the surface of an isotropically emitting continuum source should apparently accumulate in the star's magnetic polar regions before annihilation. Here a window should exist in the opaque magnetosphere within a solid angle around the star's magnetic moment through which the annihilation radiation from the stored plasma will escape in a collimated beam (cf, e.g., Katz, 1982).

The annihilation lines are observed in about 10-15% of the gamma-ray bursts. One may suggest that this frequency corresponds to a difference between the directional patterns of the annihilation and continuum emission. Accordingly, the actual ratio for the energy emitted in the two components will drop down to  $S_1/S_c \sim 0.1 - 0.4$ .

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