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UNTHERMALIZED POSITRONS IN GAMMA-RAY BURST SOURCES

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Abstract. The spectra of the broadening 0.511-MeV annihilation line produced by high temperatures was calculated in the case of unthermalized plasma; i.e., $T_{e^+} \neq T_{e^-}$. The flattening in the spectrum of the annihilation lines for large differences of electron and positron temperatures is a strong indication that the observed features of the hard-tailed spectrum of the gamma bursts can be well described by annihilation of unthermalized positrons.

We propose the charge separation occurring in Eddington limited accretion onto a neutron star or the one-photon pair production in strong magnetic fields as a mechanism for the production of unthermalized positrons in the sources of gamma bursts.

From the best fit of experimental spectra by our model, the parameters of sources for which the regions with different plasma temperatures can exist is evaluated.

1. Introduction. The gamma-ray bursts are short flashes of hard photons with an energy of 1 keV a to few tens of MeV. The gamma-ray bursts are bright, energetic, short-lived phenomena that are characterized by extremely hard spectra. The spectroscopic study of gamma-ray burst spectra on the Solar Maximum Mission (SMM) satellite [1,2] have provided a rich materials avenue towards the understanding the origin of these events. For detailed discussions of the experimental data of gamma-ray bursts, see review articles [2,3,4,5].

The major characteristic of gamma-ray bursts are as follows [3]:

1. The bursts are divided by their duration into two classes: short (< 1 s) and long (1 s to a few minutes).
2. The continuum spectra of bursts evolve rapidly with time.
3. The absorption features in the energy range of 30-100 keV are, in most cases, the strongest in the initial phase of the burst.
4. The broad annihilation lines of 350-450 keV are also the strongest at the beginning of the burst or at intense peaks of the time profile.
5. The total energy release in a gamma-ray burst is not constant; it increases approximately in proportion to the time duration of the event.
6. Gamma-ray bursts may be accompanied by intense X-ray emission and optical flashes.

The localization of gamma burst sources are not clear yet, but the log n (number of events) versus log N_{max} (maximum count rate in the time profile) plots are in full agreement with an isotropic distribution of the sources over the celestial sphere. The above argument prefers a Galactic origin of gamma bursts. Neutron stars are proposed as a candidate for that source distribution. The lines in the 30-100 keV region have been interpreted as broad cyclotron scattering in a strong magnetic field. Emission features in the 350-450 keV range have been interpreted as gravitationally redshifted annihilation e^+e^- lines produced near the surface of neutron stars. Hard power-law tails observed in the spectra of gamma bursts continue in some cases to at least ≈10 MeV. The existence of such high-energy photons and cyclotron absorption-line spectra have caused difficulty in the construction of self-consistent models of gamma burst sources. The high-energy emission region should be nearer to the neutron surface than the cyclotron absorption region in the case of interpreting observations of annihilation lines as gravitational redshifts. Moreover, the detailed analysis of relations between redshifted annihilation lines and their widths in observed gamma burst spectra shows significant disagreements when thermal pair dominant plasma annihilation has been assumed [6].

In this paper, we propose annihilation of unthermalized plasma ($T_{e^+} \neq T_{e^-}$) as the mechanism of producing gamma-ray burst spectra with line e^+e^- and hard-tail features. In that case, the redshifts of line e^+e^- are mainly due to kinematics of the annihilation process, so the relativistic emission region can be located on larger distances than absorption from the surface of a neutron star. The spectra with hard tails measured by KONUS, SMM and HEAO A-4 experiments have been fitted by thermal bremsstrahlung in soft-energy regions, and in annihilation lines of unthermalized plasma in hard-energy regions. From the best fit, we have evaluated the temperature of electrons T_{e^-}, positrons T_{e^+} and the clumpiness parameter of gamma-ray burst sources.

2. The spectra from annihilation. The broadening of the annihilation line 0.511 MeV can be produced by high temperatures, a strong magnetic field and Doppler shift due to bulk

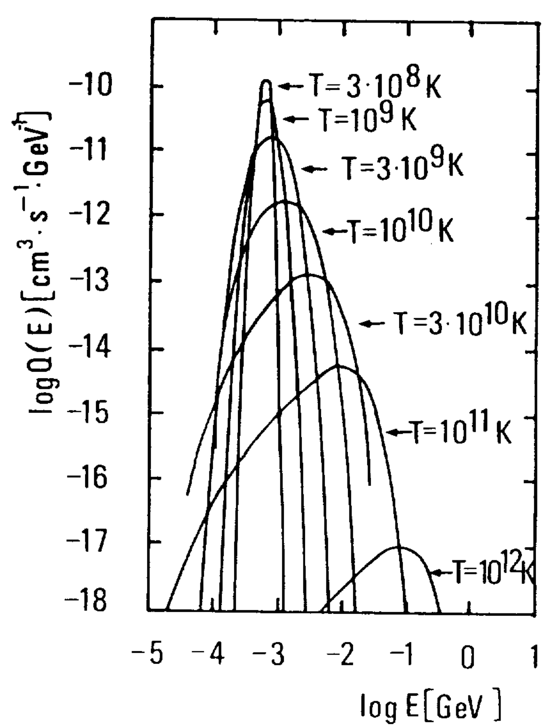

Fig. 1.

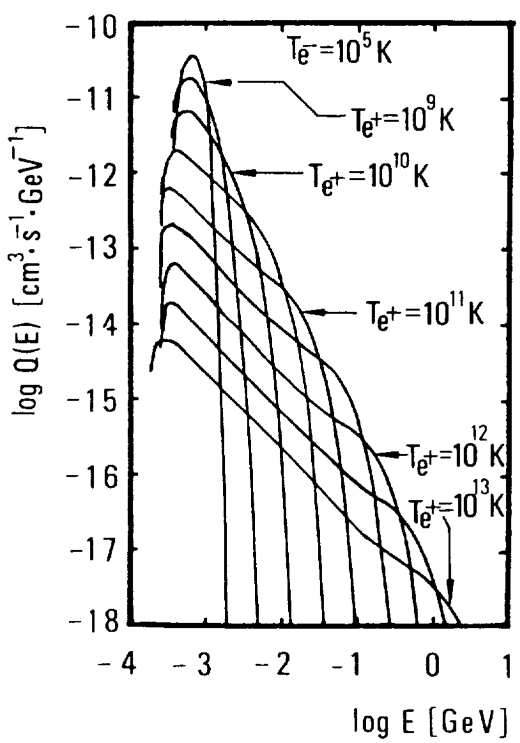

Fig. 2.

motion and the gravitational field. Recently we have calculated the spectra of annihilation lines for two cases: thermalized $T_{e^-} = T_{e^+}$ [7] and unthermalized $T_{e^+} \neq T_{e^-}$ [7]. Figure 1 shows spectra for a thermalized plasma. Figure 2 shows spectra for an unthermalized plasma with electron temperatures of 10^5 K and selected temperatures of positrons. The peak energies and widths of annihilation spectra are different in the case of unthermalized plasma in comparison with annihilation spectra for equal temperatures of electrons and positrons [8,9].

We should note that the peak energy in the spectra is not blueshifted when the temperature positron increases, but in fact, it even decreases below 0.511 MeV. For large differences between component temperatures, the peak energy approaches the value $m_e/2$.

Moreover, the spectra from unthermalized plasma at that point are harder and approach the power-law type with a power index ≈ 1. The spectra indicate similar features as observed in gamma-ray burst spectra with hard tails.

3. Models of gamma burst source. Recently the states of plasma in gamma burst sources have been investigated in many papers. The main question is, when can the line be seen? As was shown by Svensson [10] and Zdziarski [11], the annihilation line is not expected from plasma in the pair equilibrium; i.e., the pair annihilation rate balances the pair production rate. Moreover, the gamma-ray burst spectra cannot be explained by an optically thick thermal model with plasma in a weak magnetic field; i.e., $B << B_{cr}$ (magnetic field B is much lower than critical $B_{cr}=4.413\times10^{12}$ Gs). For plasma in a magnetic field $B \geq B_{cr}$, one-photon pair e^+e^- production and annihilation rates should be included. Harding [12] shows that a thermal model of gamma bursts with pair production and annihilation in a strong magnetic field requires a maximum source size which is much smaller than a neutron star radius. Moreover, the time scale of synchrotron emission in the gamma-ray burst sources in a magnetic field above 10^{12} Gs is on the order of less than 10^{-16} s. In that case, the synchrotron emission dominates the annihilation line. The above results show that in both cases, a low and strong magnetic-field thermal, optically thick model with plasma in equilibrium is not convenient for explaining all features in gamma-ray burst spectra. We propose a thermal bremsstrahlung, optically thin model of gamma bursts with unthermalized plasma $T_{e^+} \neq T_{e^-}$. The continuum component of the spectrum is due to bremsstrahlung of a hotter source region but the relativistic component is due to annihilation of a hotter plasma of positrons with a cooler plasma of electrons. The region of continuum emission and the relativistic component are separated. The annihilation region can be placed far from the neutron star surface. This supports the fact that the burst spectra do not cut-off above a few MeV and indicates that few high-energy gamma rays are eliminated by photon-photon or one-photon pair production in the magnetic field. The photon beaming along magnetic field lines avoids these difficulties. In our proposition, the annihilation line is redshifted due to kinematics. The unthermalized plasma can exist in the case of turbulent motion or additional heating of positrons or electrons. Figure 3 shows the annihilation time of unthermalized plasma (full lines) and relaxation time (broken line) for plasma with a concentration of $n_{e^+}=n_{e^-}=10^{20}$ as a function of temperature. From comparison of those times, we can conclude that annihilation time is shorter than the relaxation time if the temperature of the electrons is less than 10^8K and the temperature of the positrons is greater than 10^{10}K. For both types of models of gamma bursts: i) accretion matter on neutron star [13], and ii) thermonuclear explosion [14], a hot plasma with a temperature $>10^9$K is predicted.

In the accretion model recently proposed by Colgate and Petschek [13], details of producing unthermalized plasma were discussed in our paper [7,15]. We have proposed that the charge separation in the matter of Eddington limited accretion onto a neutron star can

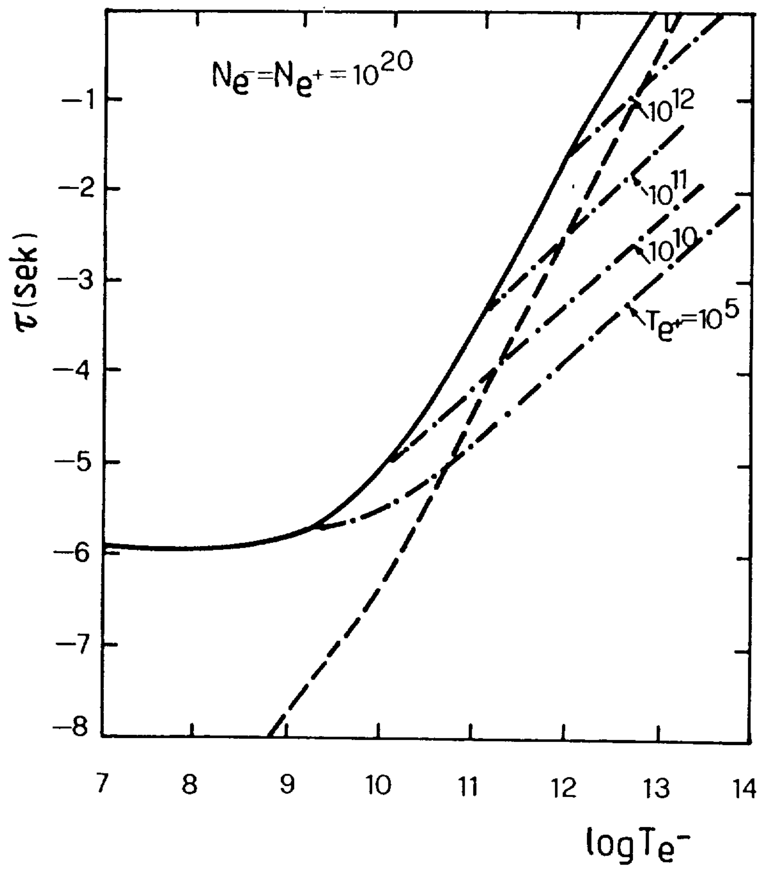

Fig. 3

produce unthermalized positrons. The scenario can be briefly described as follows: a layer of the thickness $\tau \approx 1$ falls onto the neutron star. The electrons will be pushed away from the star by the photon flux outgoing from the surface. This produces a charge separation and consequently, an electric field. The electrons are heated by interaction with the photons. Photons are produced by annihilation of positrons and by the compression caused by the matter falling onto the star surface. The pair production processes caused by photons or other particles are the source of the positrons which are accelerated not only by photon interactions, as are the electrons, but also by the electric field.

In a thermonuclear explosion model, the strong electric field generated by the motion of matter in a magnetic field, accelerated electrons up to relativistic energies.

In a strong magnetic field, the electron energy is converted to the hot pair dominated plasma. The plasma is considered to occupy a region of size R[cm], which is in a constant homogeneous magnetic field of strength $B' = B/B_{cr}$, ($B_{cr} = m^2 \cdot c^3/e\hbar = 4.414 \times 10^{13}$Gs). The pair plasma's equilibrium state is determined by its temperature, $T^*_- = kT/mc^2$ (mc^2 is the electron rest energy) and the values of B' and R. In order to calculate the positron concentration n, we made the following assumptions: i) the plasma is confined, so that positrons do not escape before annihilation; ii) the pair annihilation occurs by the two-photon process in unthermalized plasma; iii) one-photon pair production by synchrotron photons dominates over photon-photon and photon-particle processes (for some parameters of plasma it is a good approximation [16]; and iv) the electrons with temperature T^*_- have an isotropic Maxwellian energy distribution.

a) Photons. The source of photons is the synchrotron emission of thermal electrons ($T^*_- < 1$). The photon production spectrum was obtained from the emissivity of the synchrotron radiation [17], and is done by formula:

$$n_\gamma(E,\Omega) = n_- \cdot \frac{2^{3/2} \cdot \pi \cdot r_e}{3 \cdot c} \cdot \left(\frac{m \cdot c^2}{h}\right)^2 \cdot A(T^*_-) \cdot T^*_- \cdot \exp\left\{ -\left(\frac{4.5}{\sin\theta} \cdot \frac{1}{T_-^{*2}} \cdot \frac{E}{B'} \right)^{1/3} \right\},$$

where: θ is the angle between the emitted photon momentum and magnetic field line, c - velocity of light, n- concentration of electrons, $A(T^*_-)$ - normalization constant, $E=E_\gamma/mc^2$ is the photon energy in mc^2 units, and $r_e=e^2/mc^2$ is the classical electron radius.

We have evaluated the photon density by solving simple diffusion equations, taking into account photon escaping time and one-photon pair creating rate.

b) <u>Positrons</u>. The synchrotron photon spectrum was taken to determine the rate of pair production by the one-photon process:

$$R_{1\gamma}=\int d\Omega\cdot\int_{E_{min}} n_\gamma(E,\Omega)\cdot r_{1\gamma}(B',E,\Omega)\cdot dE,$$

where: $n_\gamma(E,\Omega)$ - the photon spectrum, $r_{1\gamma}(B',E,\Omega)$ - the rate of pair production per photon of energy E.

The spectra of positrons was calculated using the formula:

$$\frac{dR_{1\gamma}}{dE_+} = \frac{1}{2}\int d\Omega\cdot\int_{E_{min}}^{\infty} n_\gamma(E,\Omega)\cdot\frac{r_{\gamma B}(\varepsilon)}{d\varepsilon}\cdot\frac{d\varepsilon}{dE_+}\cdot dE\ ,$$

where: $\varepsilon=E_+/E$ is the fractional energy of one particle in the pair, $E_{min}=E_+ +1/\sin(\theta)$, $r_{\gamma B}(\varepsilon)$ is the pairs production rate for an individual photon.

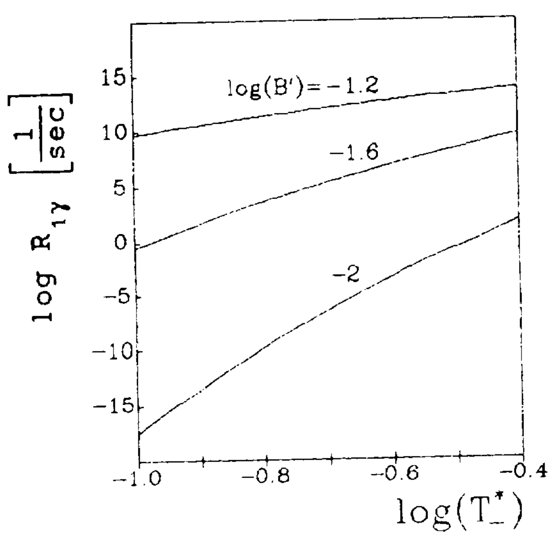

Fig. 4. The rate of one-photon pair production by electrons synchrotron emission as function of temperature T^*_- for the different values of magnetic field strength and R=1cm.

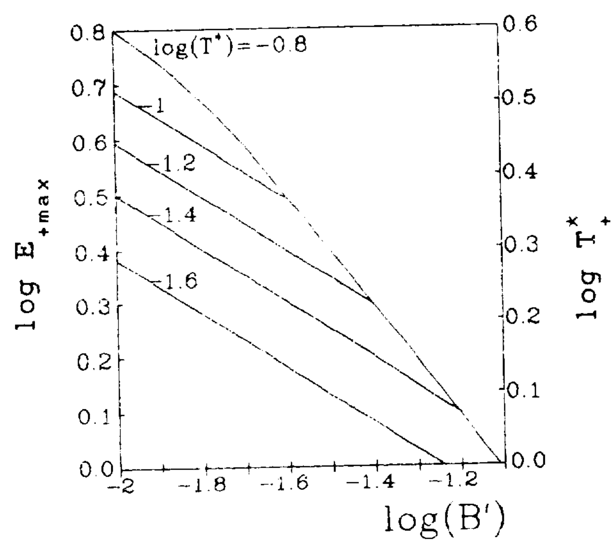

Fig. 5. The peak energy of positrons in units $E^*_+=E_+/mc^2$ (left hand scale) and temperature of positrons (right hand scale) as a function of magnetic field.

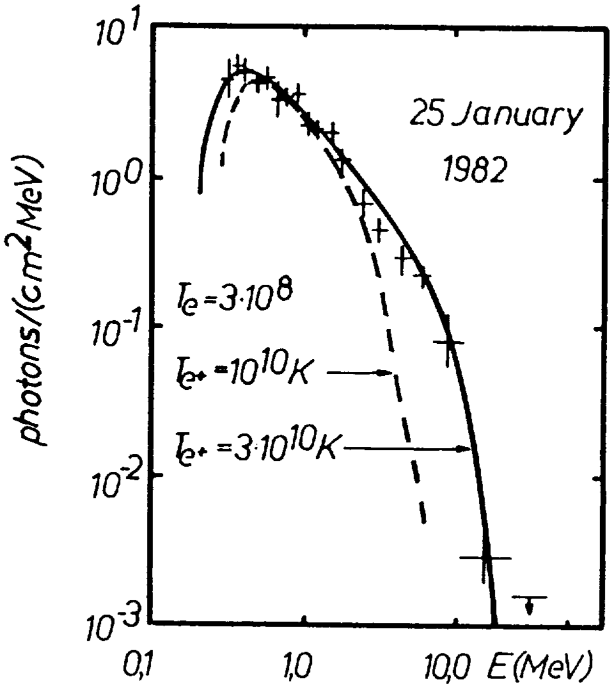

Fig. 6

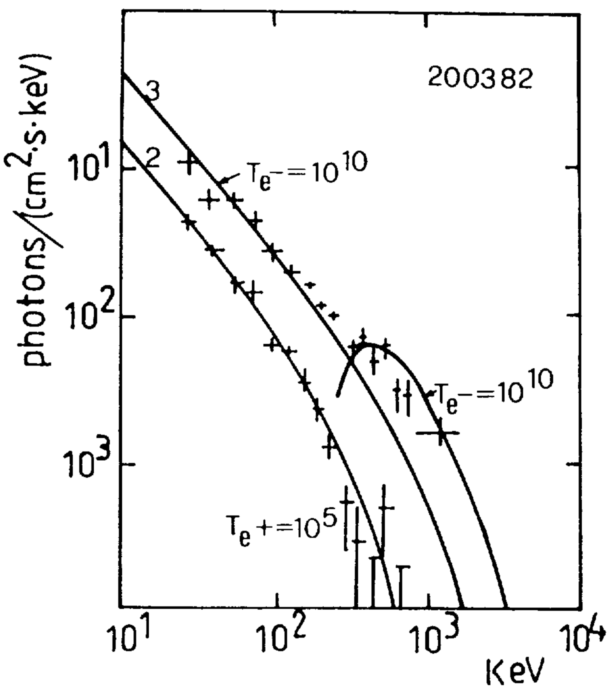

Fig. 7

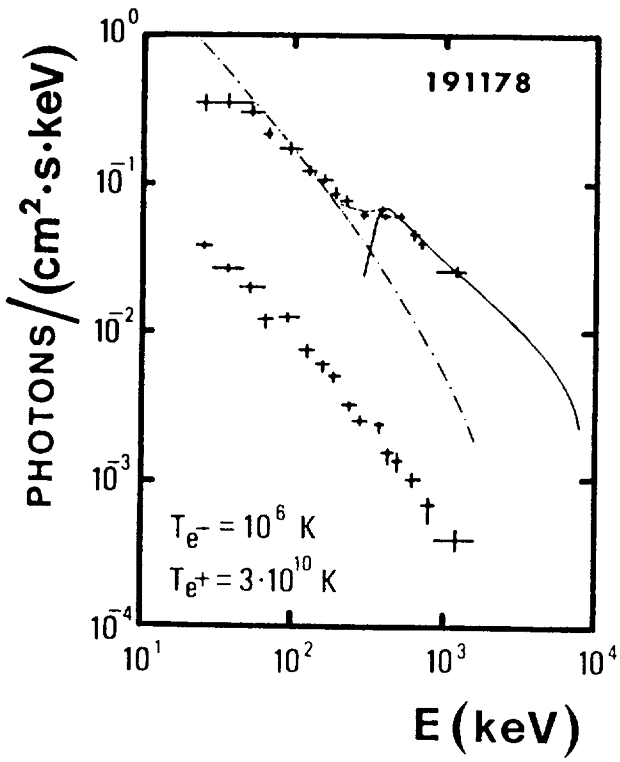

Fig. 8

Because of the threshold of the one-photon pair production process, the positron spectra has a peak at some energy. From this peak energy, we have evaluated the temperatures in units $T_+^* = kT_+/mc^2$. The positron temperature is greater than (30-60) times the temperature of parental electrons. The generated pairs rapidly lose their transfer energy by synchrotron emission. Before annihilation they move along magnetic field lines at a large distance from a neutron star surface where the magnetic field is weaker and the plasma is cooler. Hot positrons annihilate with cold electrons. The photons can escape from the magnetosphere without appreciable attenuation.

4. The results. Figures 6, 7 and 8 show the spectra of two gamma-ray bursts described by our model. The temperatures of the hot and cold components are indicated on the graphs. The efficiency of bremsstrahlung emission is dependent on the concentration squared (n^2 hot component), but annihilation is proportional to the product of (n_e-n_e+). Thus from the best fit of experimental data, it is possible to evaluate the clumpiness parameter defined as:

$$f \equiv \frac{4 \cdot \langle n_e + \cdot n_e - \rangle}{\langle n \rangle^2},$$

where $n = n_e + + n_e -$.

In Table 1 we have collected parameters of 9 gamma-ray burst sources evaluated from the best fit of experimental data by our model.

Table 1.

	GRB	T_e+	T_e-	f
1	19.04.80	10^{10}-$3 \cdot 10^{10}$	$3 \cdot 10^9$	$6.3 \cdot 10^{-3}$
2	19.11.80	10^{10}-$3 \cdot 10^{10}$	$3 \cdot 10^9$	0.10
3	06.04.79	$<10^8$	10^{10}	0.41
4	31.12.81	$<10^8$	$3 \cdot 10^9$	0.02
5	25.03.78	$<10^8$	10^{10}	0.41
6	20.03.82	$<10^8$	10^{10}	0.37
7	13.01.79	$<10^8$	10^9	$1.3 \cdot 10^{-3}$
8	08.09.82	$<10^8$	$3 \cdot 10^9$-10^{10}	0.33
9	19.11.78	$3 \cdot 10^{10}$	$<10^8$	0.88

5. Conclusions. The detailed analysis shows that in short time scales, the unthermalized-pair-dominant plasma can exist. The annihilation time scale is shorter than the bremsstrahlung time scale, when temperatures of components are as follows:

$T_e- < 10^8$K and $T_e+ > 10^{10}$K or $T_e+ < 10^8$K and $T_e- > 10^{10}$K.

The spectra of gamma bursts with a hard tail are very well described by a thermal bremsstrahlung (continuum component) and the annihilation line of an unthermalized plasma. From a best fit of our spectra to experimental data, it is possible to evaluate the temperatures of electrons and positrons and the ratio of concentration (Table 1). The temperatures of electrons and positrons evaluated from the best fit satisfy the condition of unthermalized plasma.

The Gamma Ray Burst spectra from BATSE on the GRO can support or reject our model.

6. Acknowledgements. This work was sponsored by Polish Ministry of Education.

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