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F.A.AHARONIAN, A.M.ATOYAN, R.A.SUNYAEV

THE ANNIHILATION SPECTRUM OF RELATIVISTIC ELECTRON-POSITRON PLASMA

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Ф.А.АГАРОНЯН, А.М.АТОЯН*, Р.А.СЮНЯЕВ**

СПЕКТР АННИГИЛЯЦИОННОГО ИЗЛУЧЕНИЯ ЭЛЕКТРОННО-ПОЗИТРОННОЙ РЕЛЯТИВИСТСКОЙ ПЛАЗМЫ

Впервые получено выражение для спектра аннигиляционного излучения моноэнергетических изотропно распределенных электронов и позитронов. Исследован спектр аннигиляционного излучения электронно-позитронной плазмы в широком интервале температур. Проведено сравнение интенсивности этого излучения с тормозным излучением и показано, что для температур $kT \lesssim 3mc^2 (e^-e^+)$ плазма преимущественно охлаждается в результате процесса аннигиляции. Отдельно рассматривается частный случай аннигиляции надтепловых позитронов на покоящихся электронах. Проводится обсуждение возможных астрофизических приложений полученных результатов.

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*) Ереванский государственный университет.

**) Институт космических исследований.Москва.

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Yerevan Physics Institute

Yerevan 1980

...an State University

... Research Institute, Moscow

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F.A.AHARONIAN, A.M.ATOYAN, R.A.SUNYAEV

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In the present work the photon spectrum produced in the two-photon annihilation process of the relativistic electron-positron pairs is studied and possible astrophysical applica tions are discussed.

1. The differential intensity of the two-photon annihilation

On the annihilation of electron and positron with fixed four-vector momenta $P_-^{(4)} = (\vec{P}_-, i\mathcal{E}_-)$ and $P_+ = (\vec{P}_+; i\mathcal{E}_+)$ respectively, the photon with definite energy is produced in the given direction of observation. The second photon is emitted in the direction to provide the conservation law:

$$K^{(4)} + K_1^{(4)} = P_-^{(4)} + P_+^{(4)} \tag{1}$$

where $K^{(4)} = (\vec{K}, i\omega)$ and $K_1^{(4)} = (\vec{K}_1, i\omega_1)$ are four-vector momenta of photons.

The differential cross section of the process averaged over polarizations is [1]

$$d\sigma = r_0^2 \frac{\omega^2 d\Omega}{J \varkappa_0} \left(4A - 4A^2 + B\right), \qquad (2)$$

where

$$A = \left(\frac{1}{\varkappa_1} + \frac{1}{\varkappa_2}\right), \qquad B = \left(\frac{\varkappa_1}{\varkappa_2} + \frac{\varkappa_2}{\varkappa_1}\right)$$

$$\varkappa_1 = -2P_-^{(4)} K^{(4)}, \qquad \varkappa_2 = -2P_+^{(4)} K^{(4)} \qquad (3)$$

$$\varkappa_0 = \varkappa_1 + \varkappa_2, \qquad J = V'\varepsilon_+\varepsilon_- = \sqrt{[P_+^{(4)} P_-^{(4)}]^2 - 1}$$

In (2) and (3) we take $m_e = c = \hbar = 1$. r_0 is the electron classical radius, $\varkappa_1$ and $\varkappa_2$ are relativistic invariants; V' is relative velocity of colliding electrons and $d\Omega$ is the solid angle of photon emitted.

It should be noted that the cross section (2) is correct for velocities $V' \gtrsim 2\pi\alpha$ (α = 1/137) corresponding to kinetic energy higher than 1 KeV. For $V' < 2\pi\alpha$ it is necessary to take into account the Coulomb corrections [2]. Further on we shall consider the annihilation of electrons of energies $\geqslant$ 1 KeV.

From the conservation law (1) it follows that for the fixed electron and positron momenta $\vec{P}_-$ and $\vec{P}_+$ the photons in the given direction have got δ-function energy distribution. But if the electrons have some momentum distribution $f_\pm(\vec{P}_\pm)$ in the observer's direction, one obtains a broad spectrum.

Consider now the annihilation spectrum of isotropically distributed monoenergetic electrons and positrons with total energies ε_- and ε_+. In order to find the radiation spectrum we should average the cross section (2) over solid angles of colliding electrons $d\Omega_-$ and $d\Omega_+$ taking into account the current $j = V' f(P_-) f(P_+)$.

We denote by $q^{(4)} = (\vec{q}, i\varepsilon) = P_+^{(4)} + P_-^{(4)}$ the total four vector momentum of electrons and by θ the angle between $\vec{q} = \vec{P}_- + \vec{P}_+ \omega$ and photon momentum $\vec{K}$ ("scattering" angle). Then it is clear that for $\varepsilon = \varepsilon_- + \varepsilon_+$ fixed the photon energy depends only on $q = |\vec{q}|$ and θ . Indeed. writing Eq.(1) as $K^{(4)} - q^{(4)} = - K_1^{(4)}$ and taking its square we obtain

$$\cos\theta = \frac{q^2 - \varepsilon^2 + 2\varepsilon\omega}{2q\omega} \tag{4}$$

$$\omega = \frac{\varepsilon^2 - q^2}{2(\varepsilon - q\cos\theta)} \tag{4a}$$

Therefore, in further calculations it is convenient to use independent vector variables $\vec{q}$ and the smallest of momenta $\vec{P}_-$ and $\vec{P}_+$ instead of $\vec{P}_-$ and $\vec{P}_+$. For certainty we suggest $|\vec{P}_-| \leq |\vec{P}_+|$. Then for any $\vec{P}_-$ and any unit vector $\vec{i} = \vec{q}/q$ we can unambiguously satisfy the requirement $\vec{q} = (P_- + P_+) \uparrow \vec{i}$ by appropriate choice of $\vec{P}_+$ $(\varepsilon_+ = \mathrm{const})$ Thus the vectors $\vec{P}_-$ and $\vec{q}$ are independent parameters. The direction of vector $\vec{q}$ we can determine using the angle ψ between $\vec{P}_-$ and $\vec{i}$ and axial angle between the planes $(\vec{P}, \vec{i})$ and $(\vec{K}, \vec{q})$ (Fig.1).

From the condition $q^{(4)} - p_-^{(4)} = p_+^{(4)}$ one obtains

$$\cos\psi = \frac{q^2 + 2\varepsilon\varepsilon_- - \varepsilon^2}{2qp_-} \qquad (5)$$

$$d\cos\psi = \frac{q^2 + \varepsilon^2 - 2\varepsilon\varepsilon_-}{2q^2 p_-}\, dq \qquad (5a)$$

The integration over $d\Omega_+$ and $d\Omega_-$ results in the integration over q, ω, φ using relations (4)-(5). Indeed,

$$d\Omega_+ d\Omega_- \rightarrow 2\pi\, d\cos\theta\, d\cos\psi\, d\psi \qquad (6)$$

$$0 \leq \theta \leq \pi, \quad 0 \leq \psi \leq \pi, \quad 0 \leq \varphi \leq 2\pi$$

The range of variation of q is $p_+ - p_- \leq q \leq p_+ + p_-$. For a given value q Eqs.(4) and (4a) yield

$$d\cos\theta = \frac{\varepsilon^2 - q^2}{2q\omega^2}\, d\omega \qquad (7)$$

$$\frac{1}{2}(\varepsilon - q) \leq \omega \leq \frac{1}{2}(\varepsilon + q) \qquad (7a)$$

Using (7) we obtain

$$\left(\frac{1}{4\pi}\right)^2 \iint d\Omega_+ d\Omega_- \cdots \rightarrow \frac{1}{8\pi}\int\limits_{(p_+-p_-)/2}^{(p_++p_-)/2} \frac{E\Delta + P^2}{P - P^2} \int\limits_{-P}^{P} \frac{E^2 - P^2}{P(E+x)^2}\, dx \left[\int\limits_0^{2\pi} d\varphi \ldots\right] dP, \qquad (8)$$

where

$$E = \frac{\varepsilon}{2}, \quad P = \frac{q}{2}, \quad \Delta = \frac{\varepsilon_+ - \varepsilon_-}{2}, \quad x = \omega - E \ (d\omega = dx)$$

The integration range in the (P, x) plane is plotted in Fig.2.

For derivation of differential intensity of photons it is necessary to integrate (8) over all variables excepting x i.e. to inverse the order of integration over ρ and x. Then one obtains

$$\frac{d\sigma}{d\omega}(\varepsilon_+,\varepsilon_-,\omega) = \frac{1}{8\pi P_-(E+x)^2}\int_a^b \frac{(E\Delta+\rho^2)(E^2-\rho^2)}{\rho^3}\int_0^{2\pi} dG\, d\varphi\, d\rho \qquad (10)$$

$$dG = V' d\sigma\,; \quad a = \max\left[\frac{P_+-P_-}{2}, |x|\right]; \quad b = \frac{P_-+P_+}{2} \qquad (10a)$$

$$\frac{P_+ + P_-}{2} \le x \le \frac{P_+ + P_-}{2}$$

From (10) and (10a) it follows that the annihilation spectrum is not a smooth function and has a rupture of derivative at $|x| = \frac{P_+ - P_-}{2}$.

Below we shall express the cross section (2) through x, ρ and φ variables. It is sufficient for that to express the kinematic invariants $\mathscr{X}_0$ and $\mathscr{X}_1$ through these variables.

From condition (3) we obtain

$$\mathscr{X}_0 = 2\omega(\varepsilon - q\cos\Theta),$$
$$\mathscr{X}_1 = 2\omega(\varepsilon_- - P_-\cos\Theta). \qquad (11)$$

Θ is the angle between $\vec{K}$ and $\vec{P}_-$ and can be written through Θ, ψ and φ from a simple geometrical considerations:

$$\cos\Theta_- = \cos\Theta\cos\psi - \sin\psi\sin\Theta\cos\varphi \qquad (12)$$

Finally using (4), (5), (11) and (12) we find

$$\varkappa_0 = 4(E^2 - P^2)$$

$$\varkappa_1 = \frac{2}{P^2}(E^2-P^2)(P^2+\Delta x)+\sqrt{(E^2-P^2)(P^2-x^2)[(E^2-P^2)(P^2-\Delta^2)-P^2}\ \cos\varphi \qquad (13)$$

$$\varkappa_2 = \frac{2}{P^2}(E^2-P^2)(P^2-\Delta x)-\sqrt{(E^2-P^2)(P^2-x^2)[(E^2-P^2)(P^2-\Delta^2)-P^2}\ \cos\varphi$$

For the function dG, that is under integral. we find following (2), (3) and (13) the expression

$$dG = \frac{r_0}{4\varepsilon_+\varepsilon_-}\,\frac{(E+x)^2}{E^2-P^2}\,(4A-4A^2+B)\,d\Omega, \qquad (14)$$

where

$$A = \frac{\xi^2}{2}\left[\frac{1}{t(x)+u\cos\varphi}+\frac{1}{t(-x)-u\cos\varphi}\right],$$

$$B = \frac{t(x)+u\cos\varphi}{t(-x)-u\cos\varphi}+\frac{t(-x)-u\cos\varphi}{t(x)+u\cos\varphi}, \qquad (15)$$

$$\xi^2 = \frac{P^2}{E^2-P^2}; \qquad t(x) = P^2 + x\Delta,$$

$$u = \sqrt{(P^2-x^2)(P^2-\Delta-\xi^2)}$$

The expressions (10), (14) and (15) entirely define the spectral intensity of annihilation photons for isotropically distributed electrons and positrons with energies ε_+ and ε_-. The integration by angle φ (see Appendix) leads to

$$\frac{d\sigma(\varepsilon_+,\varepsilon_-,\omega)}{d\omega} = \frac{\pi r_0^2}{8}\,\frac{1}{P\varepsilon_+\varepsilon_-}\int_{a^2}^{b^2}\frac{E\Delta+z}{z\sqrt{z}}\left[\phi(x,z)+\phi(-x,z)\right]dz, \qquad (16)$$

$$z = P^2$$

where $$\phi(x,z) = \left[(\Delta + x)^2 + \frac{z - x^2}{E^2 - z}\right]^{-1/2} \times$$

$$\times\left\{2 + \frac{2}{E^2 - z} - \frac{1}{(E^2 - z)^2} - \frac{z + x\Delta}{(E^2 - z)\left[(\Delta + x)^2 (E^2 - z) + z - x^2\right]}\right\} - \frac{1}{\sqrt{z}} \tag{17}$$

Since the initial electron and positron distributions are isotropic, the resulting photons have also to be isotropically distributed. So in (16) we have easily performed the integration over the directions of annihilating photons ($\int d\Omega \to 4\pi$).

a) Photon spectrum in general case

One can see from Eq.(16) that the spectrum is a symmetric function relative to variable $x = \omega - E$, where $E = \frac{\varepsilon_+ + \varepsilon_-}{2}$ is the mean energy coming to the each annihilation photon. This interesting result has a simple physical explanation. Indeed, from the energy conservation law it follows that if one of the photons has the energy in an interval $(\omega, \omega + d\omega)$, then the other one is in the energy range $(2E - \omega, 2E - \omega + d\omega)$. Therefore, the total number of photons in these intervals are equal.

The integration of (16) over P is given in Appendix. Here we present only the final result:

$$\frac{d\sigma^{(\varepsilon_+, \varepsilon_-, \omega)}}{d\omega} = \frac{\pi r_0^2}{8} \frac{F(x, \beta^2) - F(x, \alpha^2)}{P_- \varepsilon_+ \varepsilon_-} \tag{18}$$

where $$F(x, z) = Q \sum_{i=1}^{5} \zeta_i S_i(z)$$

$$\zeta_1 = 2E\Delta + 2\frac{\Delta}{E} - \frac{E + 3\Delta}{E^3} + \frac{1 - (\Delta + x)^2}{E^2 - x^2}, \tag{19}$$

$$\zeta_2 = 2 - (E^2 - x^2)^{-1}$$

$$\zeta_3 = \frac{2\Delta}{E^2 - x^2}\left[E x \Delta - \frac{(\Delta + x)^2 E^2 - x^2}{E}\right],$$

$$\zeta_4 = 2\,\frac{E+\Delta}{E} - \frac{E+3\Delta}{E^3}$$

$$\zeta_5 = 1$$

$$Q = \frac{2}{3}\;\frac{(E^2 - b^2)^{3/2} - (E^2 - a^2)^{3/2}}{b^2 - a^2}$$

$$S_1(z) = -\frac{2}{\tau + x^2},$$

$$S_2(z) = \ln(2\tau + x^2 + d^2)$$

$$S_3(z) = -\frac{3\tau + 2x^2 + d^2}{(\tau + x^2)^3},$$

$$S_4(z) = \frac{1}{E\sqrt{E^2 - x^2}}\ln\left|\frac{E(z + x\Delta)\sqrt{E^2 - z} - z\sqrt{E^2 - x^2}}{E(z + x\Delta)\sqrt{E^2 - z} + z\sqrt{E^2 - x^2}}\right|, \qquad \text{(19a)}$$

$$S_5(z) = \frac{E\Delta}{z} - \ln z$$

$$\tau = \tau(x, z) = \sqrt{z(z - x^2 + d^2)} + z - x^2$$

$$d = d(x) = Q\cdot(\Delta + x)$$

Quantities a and b were defined above.

For the energies of particles $\varepsilon_+, \varepsilon_- \lesssim 1{,}5\, mc^2$ a simpler expression can be obtained by expanding the functions A and B from (14) in a power Taylor series of the variable $\cos\varphi \cdot u/t$ and taking into account that $\int_0^{\pi} \cos\varphi \, d\varphi = 0$. The sufficient condition of application of this approach is the fulfilment of inequality $t^2/u^2 \gg 1$.

After simple transformations we find

$$\frac{t^2(x)}{u^2} = \frac{1}{V_-^2} + \frac{1 - V_-^2}{V_-^2} \, \frac{(E\Delta - p^2)^2}{(E-\Delta)^2 p^2 V_-^2 - (E\Delta - p^2)^2} + \frac{p^2 (E^2 - p^2)(E\Delta + x)^2}{\left[(E-\Delta)^2 p^2 V_-^2 - (E\Delta - p^2)^2\right](p^2 - x^2)}, \qquad (20)$$

$V_- = P_-/\varepsilon_-$.

This integration of (10) over φ leads to substitution $\cos\varphi = 0$ in the expressions A and B from (15). The subsequent integration over p may be carried out easily if taking into account $\frac{1}{E^2 - p^2} \simeq \frac{1}{E^2} + \frac{p^2}{E^4}$. The obtained spectrum has the form:

$$\frac{d\sigma(\varepsilon_+, \varepsilon_-, \omega)}{d\omega} = \frac{\pi r_0^2}{8 p_- \varepsilon_+ \varepsilon_-} \left[\tilde{F}(x, b^2) - \tilde{F}(x, a^2)\right]; \qquad (21)$$

$$\tilde{F}(x,z) = 2\left(E + \frac{1}{E} - \frac{1}{2E^3} - \frac{1}{E^6 \Delta} - \frac{2x^3\Delta}{E^6}\right) \frac{1}{x} \ln \frac{z - \Delta x}{z + \Delta x} +$$

$$+ 2\left(1 + \frac{1}{E^2} - \frac{1}{E^4} - \frac{\Delta}{E^5}\right) \ln (z^2 - \Delta^2 x^2) + \qquad (21a)$$

$$+ \frac{(E-x)(E^2 - 2x\Delta)\Delta}{E^6 (z + x\Delta)} + \frac{(E+x)(E^2 + 2\Delta x)}{E^4 (z - x\Delta)} - 2 \ln z + 2\frac{E\Delta}{z}.$$

In Fig.3a,b,c differential spectra of annihilation for different electron and positron energies are shown. From these figures it follows that:

1. for $\mathcal{E}_+ \neq \mathcal{E}_-$ the spectrum reveals two strong maxima symmetric with respect to the energy $\omega = \frac{\mathcal{E}_+ + \mathcal{E}_-}{2}$ corresponding to the spectrum minimum.

2. for $\mathcal{E}_+ = \mathcal{E}_-$ the spectrum logarithmically tends to infinity at $\omega \to (\mathcal{E}_+ + \mathcal{E}_-)/2$, however, this divergency does not lead to the divergency of the photon total number.

The energies corresponding to the maxima are found from the condition $4x^2 = (P_+ - P_-)^2$, i.e.

$$\omega_{1,2}^{(max)} = \frac{1}{2}\left[\mathcal{E}_+ + \mathcal{E}_- \mp (P_+ - P_-)\right]. \qquad (22)$$

The variation range of ω at fixed $\mathcal{E}_+$ and $\mathcal{E}_-$ is obtained from (7a)

$$\frac{1}{2}(\mathcal{E}_+ + \mathcal{E}_- - P_+ - P_-) \leq \omega \leq \frac{1}{2}(\mathcal{E}_+ + \mathcal{E}_- + P_+ + P_-) \qquad (23)$$

b) The radiation spectrum of positron annihilation on the rest electrons

Consider now the particular case of annihilation of the moving positron (electron) on the rest electron (positron). The spectrum can be obtained from the expression (18) by tending $P_- \to 0$. Nevertheless, it is useful to get it directly from (2), especially as in this case the calculations become considerably easy to be performed. Indeed, from kinematic invariants $\varkappa_1$ and $\varkappa_2$ for the rest electron

$P_-^{(4)} = (0, i \cdot 1)$ one obtains

$$\omega(\varepsilon_+ - P_+ \cos\theta) = \varepsilon_+ + 1 - \omega, \qquad (24)$$

$$d\cos\theta = \frac{\varepsilon_+ + 1}{P_+ \omega^2} d\omega$$

Now the cross section (2) multiplied by the positron velocity $(d\sigma \cdot V')$ should be averaged only over the directions of annihilating positron, i.e. over the angle $\frac{1}{4\pi} d\Omega_+ \to \frac{1}{2} d\cos\theta$, where θ is now the angle between vectors $\vec{P}_+$ and $\vec{K}$ $(\vec{q} \equiv \vec{P}_+)$

Finally, for the averaged differential spectrum, using (2), (3) and (24) we obtain

$$\frac{d\sigma(\varepsilon_+, \omega)}{d\omega} = \frac{\pi r_0^2}{\varepsilon_+}\Big[2\Big(\frac{1}{\omega} + \frac{1}{\varepsilon_+ + 1 - \omega}\Big) - \Big(\frac{1}{\omega} + \frac{1}{\varepsilon_+ + 1 - \omega}\Big)^2 + \qquad (25)$$

$$+ \Big(\frac{\omega}{\varepsilon_+ + 1 - \omega} + \frac{\varepsilon_+ + 1 - \omega}{\omega}\Big)\Big];$$

where

$$\frac{\varepsilon_+ + 1 - P_+}{2} \leq \omega \leq \frac{\varepsilon_+ + 1 + P_+}{2} \qquad (26)$$

Here we have performed the integration over the photon's direction $d\Omega$ as well.

Expression (25), as it should be expected, has two strong maxima which are symmetrical with respect to $\omega = \frac{\varepsilon_+ + 1}{2}$. The maxima are in two extreme points (20) and therefore have asymmetric profiles.

Finally it should be noted that annihilation of fast positrons on the rest electrons has been previously considered by Stecker [3], but the spectrum in the obvious analytical form was not obtained.

2. Astrophysical applications

Most of essential cosmic gamma-ray production mechanisms formulated for the first time in the classical paper of Morrison [4] in 1958 are generally associated with interactions of accelerated up to relativistic energies suprathermal particles (cosmic rays) with ambient gas and low-energy photon fields (2.7 K radiation, starlight, etc.). However in recent years some authors have pointed out that the intense gamma-radiation can be produced in the vicinity of compact active sources such as pulsar magnetospheres [5-7], in the accreting plasma on black holes and neutron stars [8-13], etc.

In the compact active sources positrons can be copiously produced due to various nuclear and electromagnetic interactions. The nature of cosmic positron sources now presents an increasing interest connected with difficulties which take place in the interpretation of 0.511 MeV gamma-ray line, detected recently in the galactic centre direction [14], as a result of cosmic ray bombardment of interstellar gas [15,16]. From comparison of photon intensity in the 0.511 MeV line with intensities of continuum of low energy gamma-rays [15] and X-rays [16], additional source of positrons in the Galaxy is required [17]. Possible sources of such positrons are: the decay of radionuclei synthesized at supernova and novae explosions [17], pair production in pulsar magnetospheres [5,18], massive Kerr black holes [19,20], relativistic accreting plasma (Refs 20,24).

In the case of spherical accretion the π^{+}- production in the hot proton inelastic interactions near a black hole and the following $\pi^{+} \rightarrow \mu^{+} \rightarrow e^{-}$ decays give relativistic positrons [8,10].

In the accretion disk around a black hole, when the temperature of plasma can exceed 0.1 mc^2 (for example in NGC 4151 [25]), the pair production due to $(\gamma - \gamma)$ collisions becomes a sufficient process [22-24]. For the reasonable conditions equilibrium positrom concentration may become very high and even exceeding the initial electron density in the accreting plasma [22,23], provided, of course, the positron leakage from plasma does not take place.

Annihilation radiation in such a hot plasma competes with two important radiation processes, namely with thermal bremsstrahlung (pure or comptonized, depending on optical depth of plasma) and inverse Compton scattering (comptonization) of the photons of external origin on electrons of plasma. The relative contribution of annihilation to the plasma total emission is proportional to the pair density in the plasma. Therefore, the problem of steady-state $(e^{+}e^{-})$ pair concentration in the plasma is rather significant [26]. In this paper we consider the annihilation spectrum alone.

The formation and the spectrum of annihilation line in the medium with temperature less than $\sim 10^{7}$K are studied in detail by Ramaty and co-workers [27,28].

In this work we study the annihilation spectrum of electrons and positrons with energies more than 1 KeV. This restriction allows us to neglect the Coulomb correction as well as the annihilation through bound state of positronium preliminarily formed [27].

i) Annihilation spectrum of hot Maxwellian electron-positron plasma

In the Maxwellian plasma electrons and positrons have a momentum distribution *)

$$f_{\pm}(p) \equiv n_{\pm} f_0 = \frac{n_{\pm}}{4\pi S} \exp\left(-\sqrt{p^2c^2 + m^2c^4}/\kappa T\right), \tag{27}$$

where $S = \int_0^\infty z^2 \exp\left[-(\phi^2 + z^2)^{\frac{1}{2}}\right] dz$, n_+ and n_- are electron and positron number densities, T is plasma temperature, $\phi = \frac{mc^2}{\kappa T}$, c is the speed of light and m is the rest mass of electron.

Then the differential spectrum of annihilation photons produced in the unit volume of plasma per sec is defined as

$$q(\omega) = c \iint f_+(p_+) f_-(p_-) \frac{d\sigma(\varepsilon_+, \varepsilon_-, \omega)}{d\omega} dp_+ dp_- = \tag{28}$$

$$= n_+ n_- c \iint f_0(p_+) f_0(p_-) \frac{d\sigma(\varepsilon_+, \varepsilon_-, \omega)}{d\omega} dp_+ dp_- .$$

where $\frac{d\sigma(\varepsilon_+, \varepsilon_-, \omega)}{d\omega}$ is the cross section averaged over directions of positrons and electrons (18). The integration limits in (28) can be found from (10a).

*) Further on we use m and c in obvious form.

The results of numerical calculations for plasma temperatures from 0.01 mc^2 to 50 mc^2 are presented in Fig.4. One can see that the spectrum has a maximum with halfwidth proportional to the first power of temperature T ($\sim 1.25T$) for plasma temperatures $T > 0.5\ mc^2$. For nonrelativistic temperatures the halfwidth $\sim \sqrt{T}$, that is in agreement with the previous investigations [27], performed on the basis of consideration of the broadening the 0.511 MeV annihilation line alone.

However, it should be emphasized that the correct calculations based on the cross section of the process reveal not only the broadening of 0.511 MeV line but also the shift of its maximum to higher energies:

$$\omega_{max} = \left(1 + \alpha \frac{\kappa T}{mc^2}\right) mc^2 \qquad (29)$$

where α is about 1 and slightly depends on the temperature T . In the relativistic limit α tends to 1.2 and for nonrelativistic plasma $\alpha = 0.75$.

Gamma-ray lines at 0.5 MeV (0.473 MeV [29], 0.476 MeV [30], 0.511 MeV [14] and 0.530 MeV [31]) were detected in the galactic centre direction in a number of observations. While the gamma-ray lines at 0.47 MeV and 0.511 MeV have got some interpretations (see, e.g. [32]), the line of 0.530 MeV is somewhat mysterious so far. On the other hand, as it follows from our results, this line can be readily understood supposing the annihilation takes place in the plasma with temperature 25 KeV

In Fig.4 b.c.d the electron-proton bremsstrahlung spectra obtained on the basis of Bethe-Heitler cross section (e.g. see (28. 4.1) in [1]), are presented. Fig.5 shows the radiation cooling rates of electron-positron plasma due to bremsstrahlung (curve 1) and annihilation (curve 2), as well as the rate of (e^+e^-) annihilation (curve 3). The curves correspond to the number density of electrons, positrons and protons $n_- = n_+ = n_p = 1\,cm^{-3}$.

However, to compare the contributions of annihilation and bremsstrahlung, one should take into account the electron-electron $(e^\pm - e^\pm)$ bremsstrahlung. Since the cross sections of $(e^+ - e^-)$ bremsstrahlung (in the relativistic case the $(e^+ - e^+)$ and $(e^- - e^-)$ bremsstrahlung, too) and electron-proton bremsstrahlung are the quantities of the same order of magnitude [33], we may roughly estimate the relative contributions of annihilation and bremsstrahlung of all noted kinds for the given number densities n_+, n_- and $n_p = n_- - n_+$

Let L_B and L_A be cooling rates of plasma due to bremsstrahlung and annihilation, respectively, and L_1 and L_2 be the same parameters corresponding to one pair of interacting particles (curves 1 and 2 in Fig.5). Then, in relativistic limit

$$L_A = n_+ n_- L_2$$

$$L_B \sim \left[(n_+ + n_-)^2 + (n_+ + n_-) n_p\right] L_1$$

and hence

$$\frac{L_B}{L_A} \sim \frac{2(2n_+ + n_p)(n_+ + n_p)}{n_+(n_+ + n_p)} \frac{L_1}{L_2} = 2\frac{L_1}{L_2}\left(2 + \frac{n_p}{n_+}\right)\cdots$$

In the case of low number density of positrons $n_+ \ll n_p$

$$\frac{L_B}{L_A} \sim 2\frac{n_p}{n_+}\frac{L_1}{L_2}.$$

In the opposite limit $n_+ \gg n_p$ ($n_+ \simeq n_-$, that is pure electron-positron plasma):

$$\frac{L_B}{L_A} \sim 4\frac{L_1}{L_2}$$

On the ground of calculated curves 1 and 2 in Fig.5 and the above estimates we obtain that for temperatures $kT \leq 3mc^2$ the pure electron-positron plasma ($n_+ \simeq n_-$)cools mainly due to annihilation.

ii) Annihilation spectrum of fast positrons on the ambient electrons

Consider now annihilation of suprathermal positrons (electrons) on the rest electrons (positrons) of low-temperature plasma, which also may frequently occur in astrophysics.

Most of positron sources yield nonthermal particles. A part of these positrons (about 10% for cool plasma) annihilate before thermalization. Thus, the spectrum arising in this case is of special interest.

In astrophysics the most wide-spread distributions of supra thermal particles can be fitted by power law. We considered two modifications of such spectra:

a) $$f_+(T) = AT^{-\alpha}, \quad T \geq T_0 \qquad (30a)$$
$$= AT_0^{-\alpha}, \quad T < T_0$$

b) $f_+(T) = AT^{-\alpha}$ $\quad T > T_0$ (30b)

$\quad\quad = 0$ $\quad T \leq T_0$,

where $T = (\mathcal{E} - mc^2)$ is the positron kinetic energy. The normalization coefficient A is defined so as to satisfy the energetic condition $W = \int f(T)\,\mathcal{E}\,d\mathcal{E} = 1\ \frac{erg}{cm^2}$. We assume also that the electrons are in rest. The generated radiation spectrum corresponding to ambient electron number density 1 electron/cm^3 is

$$\frac{q}{W_{n_-}} = \int f_+(T)\,\frac{d\sigma(\mathcal{E},\omega)}{d\omega}\,dT. \quad (31)$$

The results of integration are given in Figs.6,7,8.

For the positron distribution (30a) the spectrum of radiated photons has an asymmetric maximum in $\omega \sim 1 mc^2$ range. Unlike Maxwellian plasma annihilation radiation spectrum, the spectrum in this case reveals the sharp cut-off at $\omega = mc^2/2$ that follows immediately from the kinematics (26).

The positron distribution of (30b) type leads to somewhat different shape of the spectrum with two weak maxima above and below 1 mc^2. This fact is a direct consequence of the absence of low energy positrons in distribution (30b). In Fig.9 the high energetic tail ($\omega >> mc^2$) of bremsstrahlung and annihilation radiation is plotted. The comparison of these curves shows that the intensity of bremsstrahlung becomes equal to annihilation radiation in $\omega \sim 100 \div 1000$ mc^2 range depending on parameters of spectrum (30b). It should be noted that the shape of annihilation spectrum at high energies may be approximately obtained from physical considerations for an arbitrary positron distribution function $f_+(T)$. In fact, in the annihilation process of the high energy positron ($\varepsilon_+ \gg mc^2$) on the rest electron one of the produced photons (low energy) fall mainly into the energy region $\omega \sim 0.5$-$1\ mc^2$. Hence the high energy tail of annihilation spectrum can be approximated as

$$q(\omega) \sim \sigma_t(\omega = \varepsilon_+) \cdot f_+(\omega)\,, \tag{32}$$

where $\sigma_t(\varepsilon)$ is the total annihilation cross section (see, e.g. 30.4.5 [1]), which can be written for $\gamma = \frac{\varepsilon}{mc^2} \gg 1$ as

$$\sigma_t = \frac{\pi r_0^2}{\gamma}\left[\ln(2\gamma) - 1\right] \tag{33}$$

In the particular case of positron power law distribution we get

$$q(\omega) \sim \omega^{-(\alpha+1)}\left[\ln\left(\frac{2\omega}{mc^2}\right) - 1\right] \tag{34}$$

Finally we note that if monoenergetic positron and electron beams are by some way accelerated, then on their annihilation two asymmetrical peaks are formed. The energies of these peaks depend on the energies ε_+, ε_- and are given by expression (22). For the case of rest electrons one of the peaks is at $\omega \sim 0.5\ mc^2$ and the other one is at $\omega \simeq \varepsilon_+ + 0.5\,mc^2$

Thus the annihilation of the electron-positron pairs can yield gamma-ray lines of arbitrary energies. Since the relativistic electrons and positrons can be produced in pulsar magnetospheres [5,17], it is interesting to look for the "anomalous" gamma-ray lines from objects of this kind. In this connection it seems valuable to investigate in detail the spectra of these gamma bursts, which have a spectral feature within 300-500 keV [34] and are presumably associated with neutron stars (at least the gamma burst of March 5, 1979 [35-38]).

Recently, the communications of unusual gamma-ray lines detections [39,40] in two gamma ray transients have been reported. The difficulties of these lines interpretation are connected with the different kind shifts both red and ultraviolet from expected nuclear gamma-ray lines (0.511 MeV, 0.85 MeV, 2.2 MeV, 4.4 MeV, 6.1 MeV, etc.). It seems tempting to relate some of these lines to the annihilation of nonthermal electron-positron pairs. Of course, this hypothesis needs additional information, and first of all about the shape of the lines.

In connection with the possibility of electron-positron pair acceleration by radiation pressure in accreting disks [24], here arises an interesting situation of annihilation in relativistic directed (e^+e^-) beam with temperature $kT \leq mc^2$. In this case one may expect a rather narrow and shifted gamma-ray line, depending on the inclination angle of the disk.

APPENDIX

The integration $\int\limits_0^{2\pi}(4A-4A^2+B)\,d\varphi$ in cross section (10) is convenient to perform by the contour integration method after substitution of $y=\operatorname{tg}\frac{\varphi}{2}$ for φ. The functions A and B are written as

$$A=\frac{\xi^2}{2}\left\{\frac{1+y^2}{[t(x)-u]y^2+[t(x)+u]}+\frac{1-y^2}{[t(-x)-u]y^2+[t(-x)+u]}\right\},\quad \text{(A1)}$$

$$B=\frac{[t(x)-u]y^2+[t(x)+u]}{[t(-x)-u]y^2+[t(-x)+u]}+\frac{[t(-x)-u]y^2+[t(-x)+u]}{[t(x)-u]y^2+[t(x)+u]},$$

$$\int\limits_0^{2\pi}d\varphi\ldots\rightarrow 2\int\limits_{-\infty}^{\infty}\frac{dy}{1+y^2}\ldots.$$

Thus we should consider the poles $y_1=i$ and $y_2=i\sqrt{\frac{t+u}{t-u}}$ if integrating the functions (A1) over the contour in the upper halfplane $\operatorname{Im}y>0$ of complex variable y.

$$\int\limits_0^{2\pi}4A\,d\varphi=4\pi\xi^2\left[\frac{1}{R(x)}+\frac{1}{R(-x)}\right],$$

$$\int\limits_0^{2\pi}4A^2d\varphi=2\pi\xi^4\left\{\frac{t(x)}{R^3(x)}+\frac{t(-x)}{R^3(-x)}+\frac{2}{t(x)+t(-x)}\left[\frac{1}{R(x)}+\frac{1}{R(-x)}\right]\right\}\quad \text{(A2)}$$

$$\int\limits_0^{2\pi}B\,d\varphi=2\pi\left\{[t(x)+t(-x)]\left[\frac{1}{R(x)}+\frac{1}{R(-x)}\right]-2\right\},$$

$$R(x)\equiv\sqrt{t^2(x)-u^2}.$$

Using the expressions (15) of $t(x)$ and u, one obtains

$$t(x) + t(-x) = 2\rho^2 \tag{A3}$$

$$R(x) = R_\rho(x) = \rho\sqrt{(\Delta + x)^2 + \frac{\rho^2 - x^2}{E^2 - \rho^2}} .$$

The formulae (16) and (17) for cross section $d\sigma(\varepsilon_+, \varepsilon_-, \omega)d\omega$ are obtained after substituting the expressions (A2) into (10) and using variable $z = \rho^2$

Consider now how the integration of

$$I(x) = \int_{a^2}^{b^2} \frac{z + E\Delta}{z\sqrt{z}} \left[\Phi(x,z) + \Phi(-x,z)\right] dz \tag{A4}$$

in cross section (16) can be performed. The integral (A4) can be reduced to the series of the simpler components

$$I(x) = \sum_{i=1}^{5} \left[I_i(x) + I_i(-x)\right],$$

$$I_2(x) = \int_{a^2}^{b^2} \frac{E\Delta + z}{zR_z(x)} \quad \frac{2}{E^2 - z}\, dz, \tag{A5}$$

$$I_1(x) = \int_{a^2}^{b^2} 2\,\frac{E\Delta + z}{zR_z(x)}\, dz,$$

$$I_3(x) = -\int_{a^2}^{b^2} \frac{E\Delta + z}{zR_z(x)} \cdot \frac{1}{(E^2 - z)^2}\, dz,$$

$$I_4(x) = -\int_{a^2}^{b^2} \frac{(E\Delta + z)(z + x\Delta)}{(E^2 - z)^2 R_z^3(x)}\, dz,$$

$$I_5(x) = -\int_{a^2}^{b^2} \frac{E\Delta + z}{z^2}\, dz = S_5(b^2) - S_5(a^2) \equiv \tilde{S}_5(x).$$

The functions $S_5(z)$ and $R_z(x)$ are defined from (19a) and (A3), respectively. The integrals I_1, I_2, I_3 and I_4 are convenient to be expressed through $\tilde{S}_i$.

$$\tilde{S}_1(x) = \int_{a^2}^{b^2} \frac{dz}{z R_z(x)}; \qquad \tilde{S}_2(x) = \int_{a^2}^{b^2} \frac{dz}{R_z(x)}; \tag{A6}$$

$$\tilde{S}_3(x) = \int_{a^2}^{b^2} \frac{dz}{z^2 R_z(x)}; \qquad \tilde{S}_4(x) = \int_{a^2}^{b^2} \frac{dz}{(E^2 - z) R_z(x)}.$$

While the integrals $I_1(x)$ and $I_2(x)$ can be directly brought to $\tilde{S}_1(x)$, $\tilde{S}_2(x)$ and $\tilde{S}_4(x)$, for expressions $I_3(x)$ and $I_4(x)$ through $S_i(x)$ it is necessary to preliminarily integrate them by parts taking into account that at $z = (a^2, b^2)$ the function

$$R_z(x) \rightarrow t(x) = P + x\Delta \tag{A6a}$$

This results in

$$\sum_{i=1}^{5} I_i(x) \equiv F(x) = \left[2E\Delta + 2\frac{\Delta}{E} - \frac{E+3\Delta}{E^3} + \frac{1-(\Delta+x)^2}{E^2 - x^2}\right] \cdot \tag{A7}$$

$$\cdot \tilde{S}_1(x) + \left(2 - \frac{1}{E^2 - x^2}\right) \tilde{S}_2(x) + \frac{3\Delta}{E^2 - x^2}\left[E\Delta x - \frac{(\Delta+x)^2 E^2 - x^2}{E}\right] \cdot$$

$$\cdot \tilde{S}_3(x) + \left(2\frac{E+\Delta}{E} - \frac{E+3\Delta}{E^3}\right) \tilde{S}_4(x) + \tilde{S}_5(x).$$

To obtain the final expression for differential cross section of two-photon annihilation of electron-positron pair one should integrate the functions (A6). The absolute accurate analytical integration is impossible to be performed because of irrational function

$$R_z(x) = \sqrt{z\left[(\Delta + x)^2 + \frac{z - x^2}{E^2 - x}\right]} \quad \text{(A8)}$$

However, it is possible to perform this integration approximately. Note, that the function (A8) strongly depends, first of all, on the variations of (z) and $(z - x^2)$ and in a less degree on the $(E^2 - z)$, when z changes in the limits a and b (10a).

Therefore, one can hope to get good approximations for $\widetilde{S}_i$ if making the substitution of some average quantity Q^2 for $(E^2 - z)$. The functions $\widetilde{S}_1$, $\widetilde{S}_2$ and $\widetilde{S}_3$ thus transformed are reduced to rational functions by substitution $\tau = z - x^2 + \sqrt{z[z - x^2 + (\Delta + x)^2 Q^2}$. Then we obtain

$$\widetilde{S}_1(x) = Q[S_1(b^2) - S_1(a^2)],$$

$$\widetilde{S}_2(x) = Q[S_2(b^2) - S_2(a^2)], \quad \text{(A9)}$$

$$\widetilde{S}_3(x) = \frac{2}{3} Q[S_3(b^2) - S_3(a^2)],$$

where $S_1(x)$, $S_2(x)$ and $S_3(x)$ are defined by formulae (19a). The quantity Q is chosen as the average value of $\sqrt{E^2 - z}$ in the limits $a^2 \leq z \leq b^2$

$$Q = \frac{2}{3} \frac{(E^2 - b^2)^{\frac{3}{2}} - (E^2 - a^2)^{\frac{3}{2}}}{b^2 - a^2} \quad \text{(A10)}$$

For $\widetilde{S}_4$ it is more convenient to make a slightly different averaging, viz.

$$R_z(x) = \frac{\sqrt{z[(\Delta+x)^2(E^2-z)+z-x^2]}}{\sqrt{E^2-z}} \longrightarrow Q^{-1}\sqrt{z\left\{(\Delta+x)^2E^2-x^2+[1-(\Delta+x)^2]z\right\}} \tag{A11}$$

After substitution

$$\sqrt{z\left\{(\Delta+x)^2E^2-x^2+[1-(\Delta+x)^2]z\right\}} = zt'$$

and integration over t' we come to the expression

$$\widetilde{S}_4(x) = Q\left[S_4(b^2) - S_4(a^2)\right] \tag{A12}$$

where the function $S_4(z)$ is given in (19a). To find the variation limits of t' we used (A6a).

Thus, using relations (16), (A4), (A7), (A9), (A10) and (A12) we come to (18), (29) for differential cross section $d\sigma/d\omega$. It should be also noted that the comparison of the numerical integration of the expression (A7) with the formulae (A9, A12) shows that the method of approximate integration employed above ensures the accuracy of $\sim$ 3%.

After this paper was completed we learnt about Monte-Carlo calculations of annihilation spectrum in hot Maxwellian (e^+e^-) plasma, performed by A.A.Zdziarski (private communication).

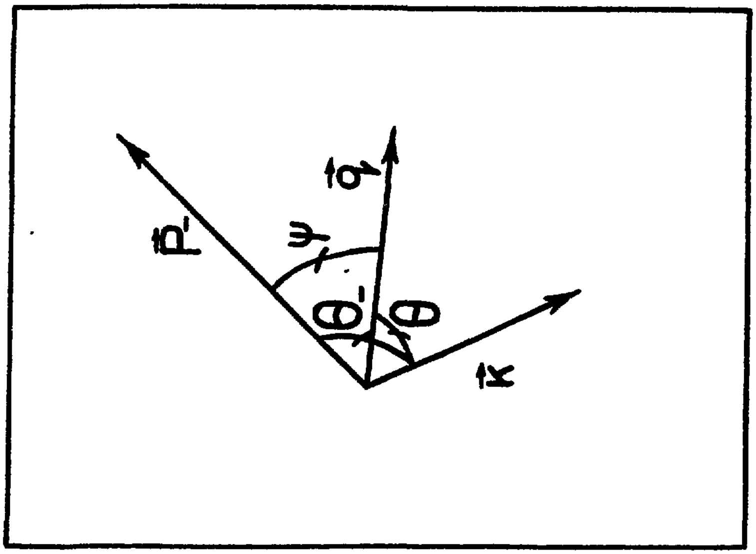

Fig.1

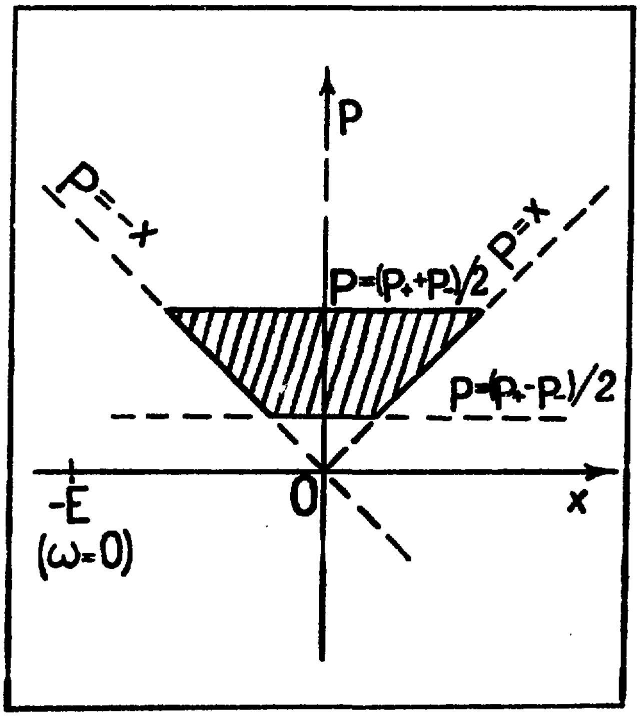

Fig.2

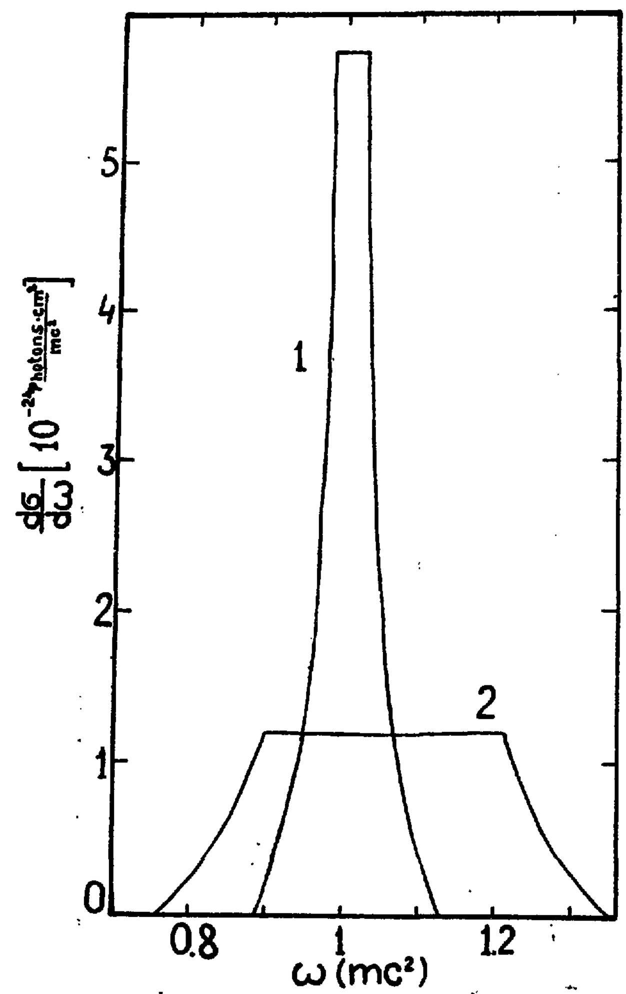

Fig.3a

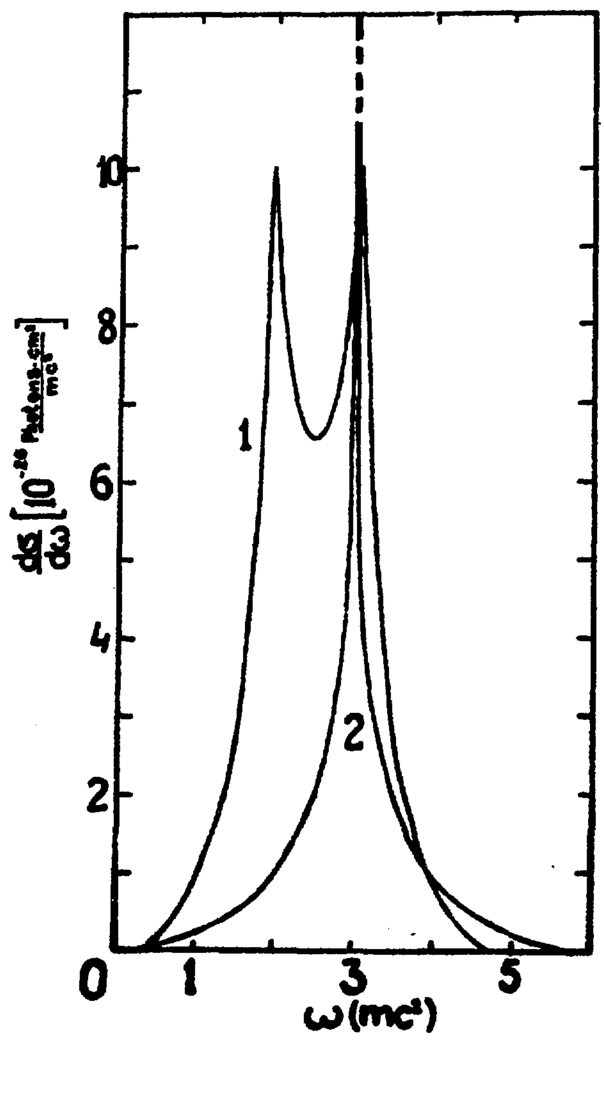

Fig. 3b

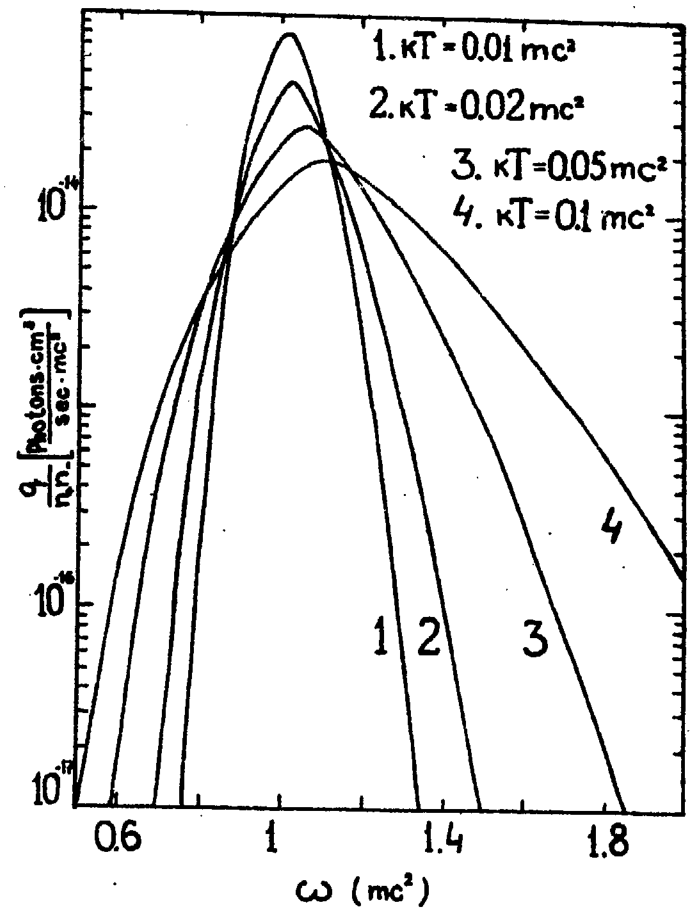
1. κT = 0.01 mc²
2. κT = 0.02 mc²
3. κT = 0.05 mc²
4. κT = 0.1 mc²
q / n₁n₂ [Photons·cm³ / sec·mc²]
ω (mc²)
0.6
1
1.4
1.8
1
2
3
4

Fig. 4a

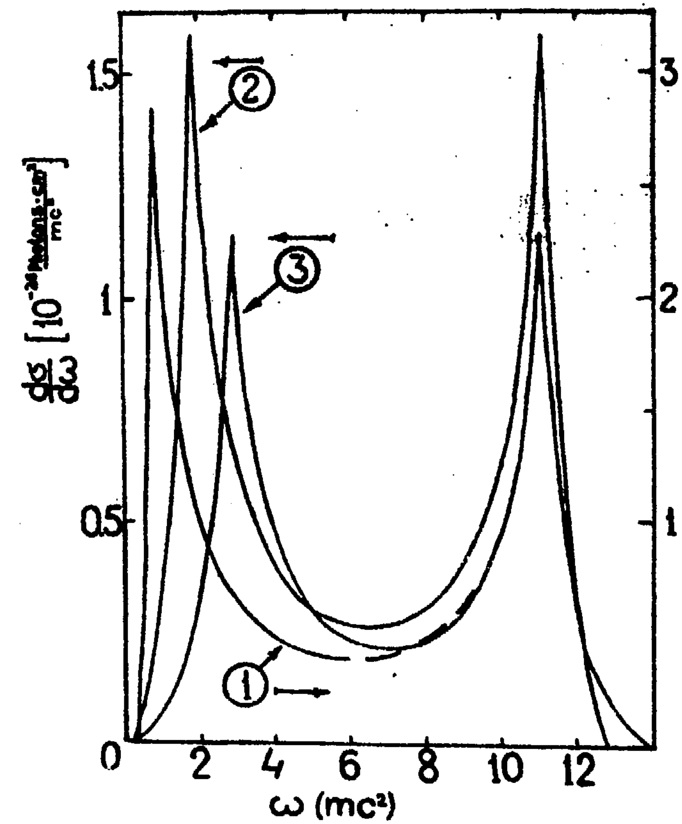
dσ/dω [10⁻²⁶ Photons·cm² / mc²]
ω (mc²)
0
0.5
1
1.5
2
4
6
8
10
12
3
2
1

Fig. 3c

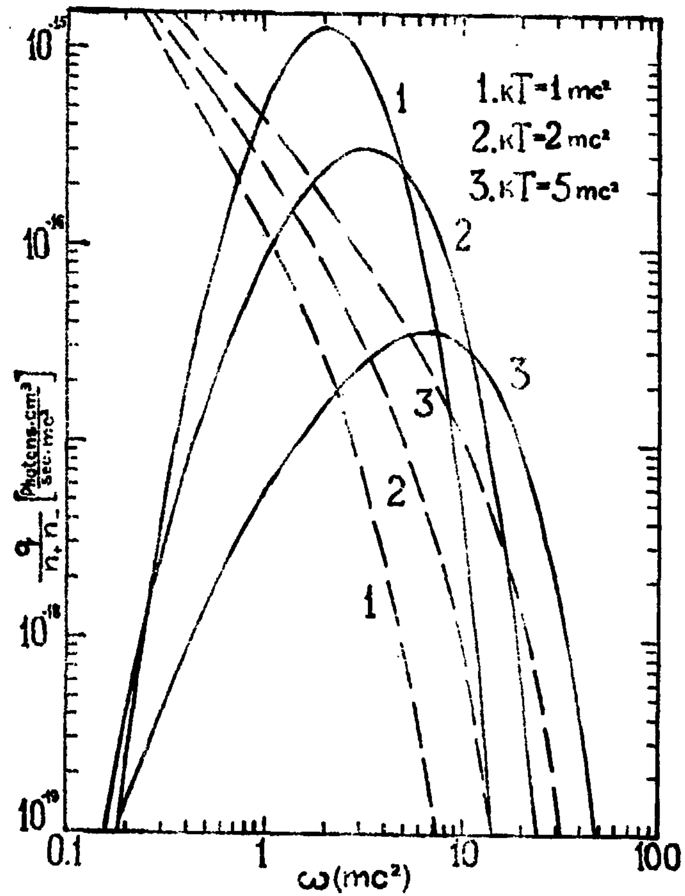
1.κT=1 mc²
2.κT=2 mc²
3.κT=5 mc²
ω(mc²)

Fig. 4c

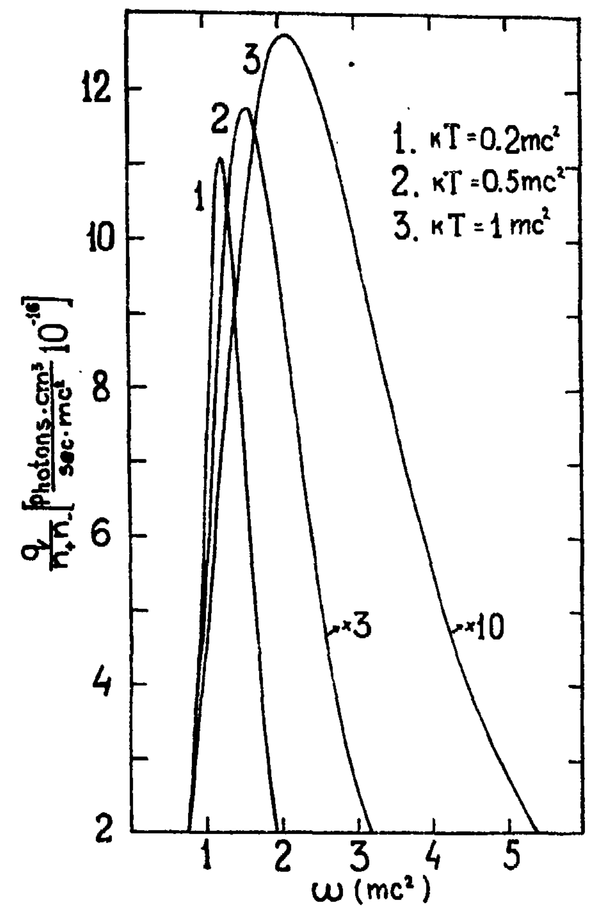
1. κT = 0.2mc²
2. κT = 0.5mc²
3. κT = 1 mc²
×3
×10
ω (mc²)

Fig. 4b

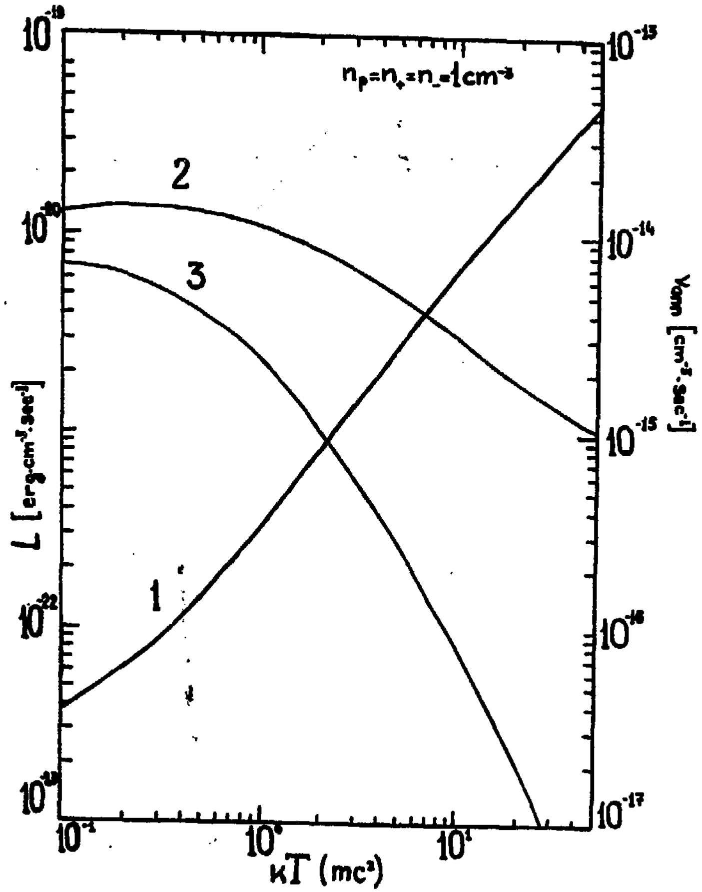
$n_p = n_+ = n_- = 1\,cm^{-3}$
1
2
3
L [erg·cm^{-3}·sec^{-1}]
ν_{ann} [cm^{-3}·sec^{-1}]
κT (mc^2)

Fig. 5

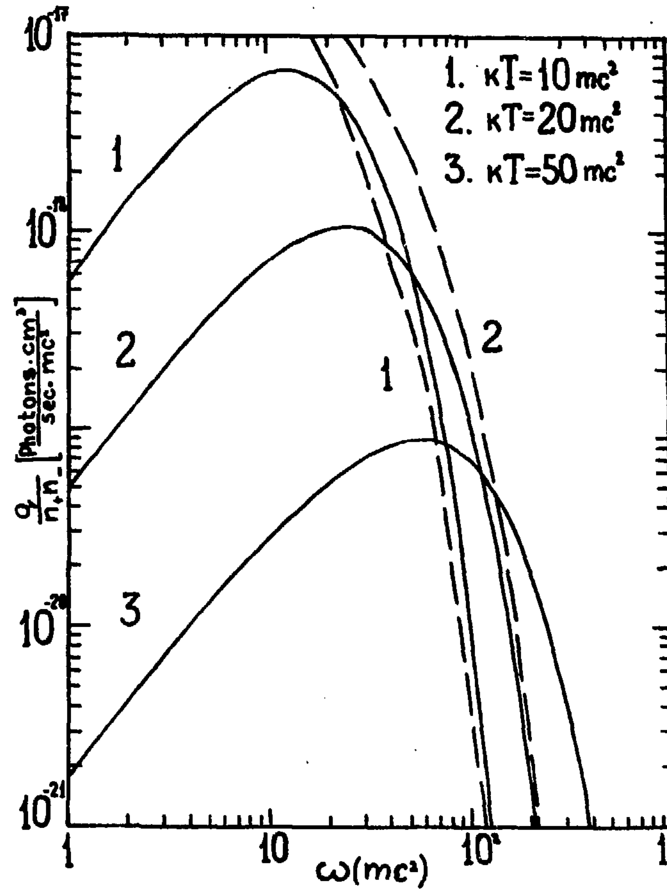
1. $\kappa T = 10\,mc^2$
2. $\kappa T = 20\,mc^2$
3. $\kappa T = 50\,mc^2$
1
2
3
$\frac{q}{n_+ n_-}$ $\left[\frac{photons \cdot cm^3}{sec \cdot mc^2}\right]$
ω(mc^2)

Fig. 4d

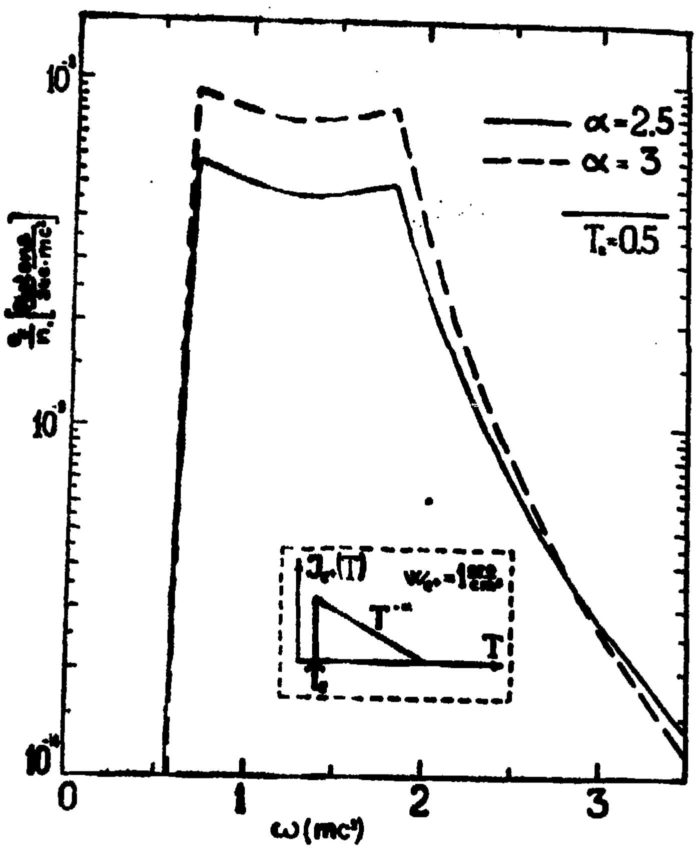

Fig.7

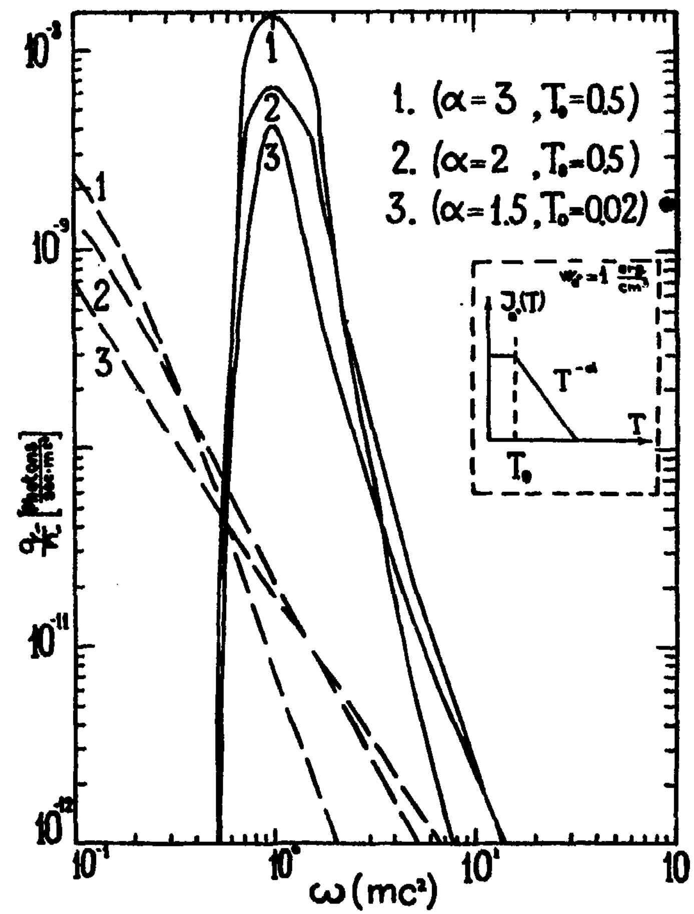

Fig.6

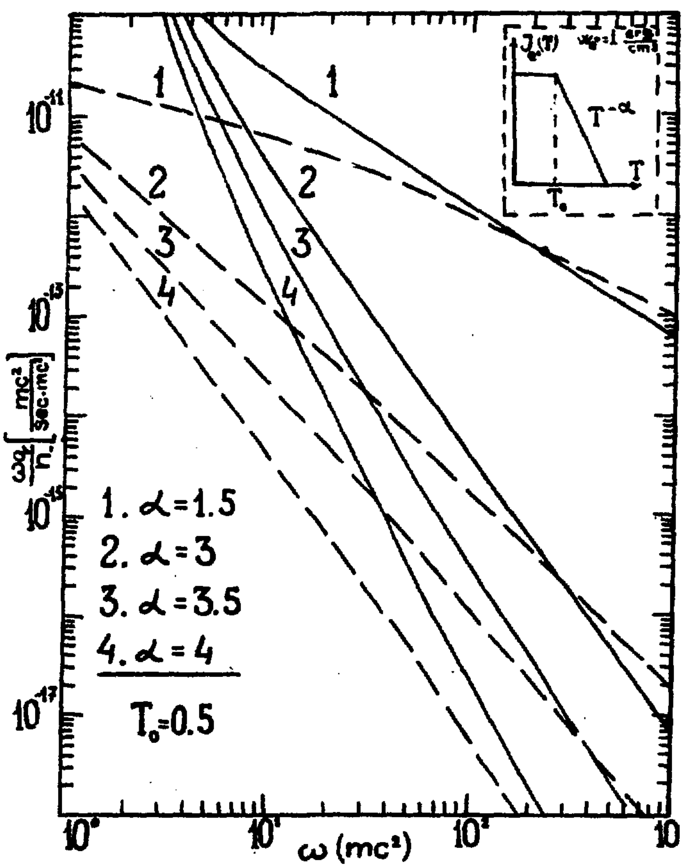

Fig.8

FIGURE CAPTIONS

Fig.1 The angles and momenta of particles participating in the reaction $e^{+} + e^{-} \rightarrow \gamma + \gamma$

Fig.2 The kinematic range of variation of ρ and x

Fig.3 Differential spectrum of two-photon annihilation, averaged over the directions of electron and positron with kinetic energies

a) 1 - $\kappa T_{+} = 0.01\ mc^2$, $\kappa T_{-} = 0.005\ mc^2$
2 - $\kappa T_{+} = 0.1\ mc^2$, $\kappa T_{-} = 0.01\ mc^2$

b) 1 - $\kappa T_{+} = 2\ mc^2$, $\kappa T_{-} = 1\ mc^2$
2 - $\kappa T_{+} = \kappa T_{-} = 2\ mc^2$

c) 1 - $\kappa T_{+} = 10\ mc^2$, $\kappa T_{-} = 0.1\ mc^2$
2 - $\kappa T_{+} = 10\ mc^2$, $\kappa T_{-} = 1\ mc^2$
3 - $\kappa T_{+} = 10\ mc^2$, $\kappa T_{-} = 2\ mc^2$

Fig.4 Plasma radiation spectrum due to annihilation (solid curves) and bremsstrahlung (dashed curves) for temperatures

a) $0.01\ mc^2$, $0.02\ mc^2$, $0.05\ mc^2$, $0,1\ mc^2$
b) $0.2\ mc^2$, $0.5\ mc^2$, $1\ mc^2$
c) $1\ mc^2$, $2\ mc^2$, $5\ mc^2$
d) $10\ mc^2$, $20\ mc^2$, $50\ mc^2$

Fig.5 Cooling rates of $(e^{+}e^{-})$ plasma due to electron-proton bremsstrahlung (curve 1), $(e^{+}e^{-})$ annihilation (curve 2) and annihilation rate (curve 3).

Fig.6 Production functions of photons due to suprathermal positron annihilation on rest electron (solid curves) and bremsstrahlung (dashed curves). Energy distribution of positrons is (30a) with parameters:
$\alpha = 3$, $kT_o = 0.5\ mc^2$ (curve 1); $\alpha = 2$, $kT_o = 0.5\ mc^2$ (curve 2); $\alpha = 1.5$, $kT_o = 0.02\ mc^2$.

Fig.7 Production functions of photons due to suprathermal positron annihilation on rest electrons. Energy distribution of positrons is (30b) with parameters:
$kT_o = 0.5\ mc^2$, $\alpha = 2.5$ (——), $\alpha = 3$ (---).

Fig.8 The high energetical tail of annihilation (solid curves) and bremsstrahlung (dashed curves) spectra. Energy distribution of positrons is (30a) with parameters
$T_o = 0.5\ mc^2$, $\alpha = 1.5$ (curve 1), $\alpha = 3$ (curve 2)
$\alpha = 3.5$ (curve 3), $\alpha = 4$ (curve 4).

REFERENCES

1 A.I.Akhiezer, V.B.Berestetskii. Quantum Electrodynamics, Interscience Publishers, New York. 1965.

2 L.D.Landau, E.M.Lifshitz, Quantum Mechanics, London. Pergamon Press, 1958.

3 F.W.Stecker, Cosmic Gamma Rays, NASA-SP-249, Washington, 1971.

4 P.Morrison, Nuovo Cimento, 7, 858, 1958.

5 P.A.Sturrock, Astrophys. J., 164, 529, 1971.

6 L.M.Ozernoy, V.V.Usov. Astron. Zh., 54, 753. 1977.

7 Ogelman et al., "Structure and Content of the Galaxy and Galactic Gamma Rays", Greenbelt, p.118. 1976.

8 G.Dahlbacka, G.F.Chapline and T.H.Weaver. Nature, 250. 36, 1974.

9 L.Maraschi, A.Treves, Astrophys. J., 218, L113, 1977.

10 P.I.Kolikhalov, R.A.Sunyaev, Astron. Zh.. 56. 338, 1979.

11 M.S.Collins. Astron.Astrophys., 74, 108, 1979.

12 R.E.Lingenfelter, R.Ramaty. Physics Today. 3, 40, 1978.

13 L.M.Ozernoy, F.A.Aharonian, Astrophys. Space Sci., 66, 497, 1979.

14 M.Leventhal, C.J. MacCallum, P.D.Stang. Astrophys. J.. 225, L11, 1978.

15 R.Ramaty, B.Kozlovsky, R.E.Lingenfelter. Astrophys. J. Suppl., July, 1979.

16 F.A.Aharonian, S.R.Kelner, V.G.Kirillov-Ugryumov, Yu.D.Kotov, Proc. 16-th Inter Cosmic Ray Conf., Kyoto, v.1, 173, 1979; F.A.Aharonian, S.R.Kelner, Yu.D.Kotov,

submitted to Astron. Astrophys.

17 R.E.Lingenfelter, R.Ramaty, Proc. 16-th Inter. Cosmic Ray Conf., Kyoto, v.1, 501, 1979.

18 P.A.Sturrock, K.B.Baker, Astrophys. J., 234, 32, 1979.

19 D.Leiter, M.Kafatos, Astrophys. J., 226, 32, 1978.

20 M.Kafatos, D.Leiter, Astrophys. J., 229, 46, 1978.

21 R.Ramaty, G.Borner, J.M.Cohen, Astrophys. J., 181, 891, 1973.

22 E.P.T.Liang, Astrophys. J., 234, 1105, 1979.

23 W.R.Stoeger, Astron. Astrophys., 61,659, 1977.

24 R.A.Sunyaev, Pis'ma v Astron. Zh., 1980, in print.

25 V.Schonfelder, Nature, 274, 345, 1978.

26 G.S.Bisnovatyi-Kogan, Ya.B.Zel'dovich, R.A.Sunyaev, Astron. Zh., 48, 24, 1971.

27 C.J.Crannel, G.Joyce, R.Ramaty, C.Werntz, Astrophys. J., 210, 582, 1979.

28 R.W.Bussard, R.Ramaty, R.J.Drachman, Astrophys. J., 228, 928, 1979.

29 W.H.Johnson et al., Astrophys. J., 172, L1, 1972.

30 W.H.Johnson R.C.Haymes, Astrophys. J., 184, 103, 1973.

31 R.C.Haymes et al., Astrophys. J., 201, 593, 1975.

32 I.L.Rozenthal, V.V.Usov, I.V.Estulin, Usp.Fiz.Nauk, 127, 135, 1979.

33 V.N.Bayer, B.M.Katkov, V.S.Fadin, Radiation of Relativistic Electrons, Moscow, 1973.

34 E.P.Mazets et al., Pis'ma v Astron. Zh., 5, 163, 1979.

35 E.P.Mazets et al., Pis'ma v Astron. Zh., 5, 307, 1979.

36 F.A.Aharonian, L.M.Ozernoy, Astron. Tsirk., 1072, 1, 1979

37 R.E.Lingenfelter, R.Ramaty, R.W.Bussard, preprint. 1979.

38 E.V.Ergma, R.A.Sunyaev, Pis'ma v Astron. Zh., 1980, in print.

39 A.S.Jacobson, J.C.Ling, W.A.Mahoney and J.B.Willett, NASA Technical Memorandum, 79619, Proc. GSFC Symp. on Gamma Ray Spectroscopy in Astrophysics, August, 1978.

40 J.Willett, J.C.Ling, W.A.Mahoney, A.S.Jacobson, 153-rd Meeting of AAS, Mexico City, January, 1979.

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Ф.А.АГАРОНЯН, А.М.АТОЯН, Р.А.СЮНЯЕВ

СПЕКТР АННИГИЛЯЦИОННОГО ИЗЛУЧЕНИЯ ЭЛЕКТРОННО-ПОЗИТРОННОЙ РЕЛЯТИВИСТСКОЙ ПЛАЗМЫ

(на английском языке)

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