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National Aeronautics and Space Administration

Goddard Space Flight Center
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ANNIHILATION RADIATION FROM A HOT e^+-e^- PLASMA

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ABSTRACT

We have studied the details of pair annihilation in hot e^+-e^- plasmas. We have calculated the annihilation rate, luminosity and spectrum of optically thin plasmas of temperatures above 10^8K by means of a Monte-Carlo simulation. For a given temperature, the spectrum is peaked at an energy equal to 0.511 MeV plus a positive definite quantity of order kT. In high temperature sources, such as gamma ray bursts, this blueshift can amount to a significant fraction of 0.511 MeV. The annihilation line is also temperature broadened: The width varies as $T^{1/2}$ for kT much less than 0.511 MeV, and as T for kT >>0.511 MeV. The widths of the 400 to 460 keV emission lines observed from several gamma ray bursts, if interpreted as gravitationally redshifted e^+-e^- annihilation, set limits on the temperatures of the pair annihilation region in burst sources. These limits ($T \lesssim 3\times10^8$K) are considerably lower than the typical kinetic temperatures ($T \gtrsim 10^9$K) of the radiating particles. The burst emission, therefore, is either nonthermal, or the pair annihilation region is spatially distinct from the site of the outburst itself.

Subject headings: positron-electron annihilation - high temperature plasmas - gamma ray bursts.

I. INTRODUCTION

Recent transient gamma ray observations have revealed emission and absorption features in many gamma ray bursts. The most commonly observed emission line, seen so far in seven gamma ray bursts (Mazets et al. 1979, Teegarden and Cline 1980, Mazets et al. 1981), and in a longer duration transient (Jacobson et al. 1978), falls in the energy range from 400 to 460 keV. This line could be gravitationally redshifted e^+-e^- annihilation produced at the surfaces of neutron stars (e.g. Ramaty, Borner and Cohen 1973, Mazets et al. 1979, Ramaty et al. 1980). That e^+-e^- pairs should, in fact, be copiously produced in gamma ray burst sources is implied by the opacities of the source regions to photon-photon pair production (Schmidt 1978, Cavallo and Rees 1978). The exact manner in which these pairs would annihilate to produce a relatively narrow line from an otherwise optically thick source is not well understood, although, as suggested by Ramaty et al. (1980) and Ramaty, Lingenfelter and Bussard (1981), synchrotron cooling before annihilation in the strong magnetic fields of neutron stars could produce an observable annihilation feature in the outer skin layer of the source region.

Clearly, much information on gamma ray burst sources and neutron stars would follow from a complete understanding of the physics of line formation in e^+-e^- annihilation. Positron annihilation in relatively cool ($<10^7$ K) media has been investigated in considerable detail by Crannell et al.(1976) and Bussard, Ramaty and Drachman (1979) who applied their results to the observed 0.511 MeV line from solar flares (Chupp et al. 1973) and the galactic center (Leventhal, MacCallum and Stang 1978, Jacobson 1981). Gamma ray burst sources, however, are likely to have temperatures considerably in excess of 10^8 K, as indicated by their observed continuum spectra. Whereas below about 10^8 K positronium formation plays a central role in determining the shape of the 0.511 MeV line (see Ramaty and Lingenfelter 1981 for a review), at the temperatures characteristic of gamma ray bursts, the bulk of the annihilations proceed directly, $e^+ + e^- \rightarrow \gamma + \gamma$. Since no intermediate bound state is produced in such annihilations, the annihilation feature peaks at an energy which equals the electron rest mass, mc^2 =511 keV, plus a positive definite quantity that depends on the kinetic energies of the annihilating pairs. This blueshift is of the order kT, and thus significant for studies of gamma ray burst sources, in particular for studies that depend on a precise determination of the gravitational redshift. The fact that the peak of the direct e^+-e^- annihilation line is temperature dependent and always above 0.511 MeV, has not been widely appreciated in the published literature.

In the present paper we calculate in detail the annihilation rate and annihilation spectrum of optically thin e^+-e^- plasmas of temperatures above 10^8K. Our results, while obtained by different kinematical and numerical techniques, agree quite well with those of a recent calculation by Zdziarski (1981). Both calculations employ Monte-Carlo simulations for the evaluation of multidimensional integrals. We study, in addition, the blueshifting of the peak of the annihilation spectrum and its broadening as a function of temperature, and we discuss the consequences of these effects on the emission lines observed in gamma ray bursts. The same calculations could also be applicable to other high energy astrophysical phenomena which involve radiation from e^+-e^- pairs, in particular active galactic nuclei and accreting compact x-ray sources. While the full understanding of the nature of e^+-e^- annihilation radiation from compact objects will require the study of radiation transfer in a relativistic plasma, a necessary ingredient in such a study is the annihilation emissivity worked out in the present paper.

II. HIGH TEMPERATURE e^+-e^- ANNIHILATION

Consider an electron-positron pair plasma in which both kinds of particles have equal densities, $n_+=n_-$, and isotropic Maxwell-Boltzman energy distributions. We shall calculate the annihilation rate and luminosity of this plasma, and the energy distribution of the annihilation radiation.

The annihilation rate per unit volume can be written as

$$R = n_+ n_- \langle\sigma(\gamma_+,\gamma_-,\mu) v_r(\gamma_+,\gamma_-,\mu)\rangle, \qquad (1)$$

where σ and v_r are the annihilation cross section and relative velocity of a positron and electron with Lorentz factors γ_+ and γ_-, respectively, and angle $\cos^{-1}\mu$ between their directions of motion. Equation (1) is averaged over a uniform distribution for μ, and over a Maxwell-Boltzman distribution for γ_+ and γ_-,

$$F(\gamma) = (\alpha/K_2(\alpha))\beta\gamma^2 e^{-\alpha\gamma}, \qquad (2)$$

where $\beta = (\gamma^2-1)^{\frac{1}{2}}/\gamma$, $\alpha = mc^2/kT$, and K_2 is the modified Bessel function of the second kind.

To evaluate equation (1) we use the invariance property of cross sections, $\gamma_+\gamma_-\sigma v_r$ = invariant (Landau and Lifschitz 1970), and the annihilation cross section in the center-of-momentum (CM) frame of the two particles (Heitler 1954)

$$\sigma^* = \frac{\pi r_0^2}{4\gamma^{*2}\beta^*}\left[2(\beta^{*2}-2)+\frac{3-\beta^{*4}}{\beta^*}\log\frac{1+\beta^*}{1-\beta^*}\right]. \quad (3)$$

Here $r_0 = e^2/mc^2$, γ^* is the positron or electron Lorentz factor in the CM frame and $\beta^* = (\gamma^{*2}-1)^{\frac{1}{2}}/\gamma^*$ Thus,

$$R = n_+n_-\langle\sigma^*(\gamma^*)2c\beta^*\gamma^{*2}/(\gamma_+\gamma_-)\rangle, \quad (4)$$

where the right hand side is a function of γ_+, γ_- and μ only, since

$$\gamma^* = 2^{-\frac{1}{2}}[1+\gamma_+\gamma_- -(\gamma_+^2-1)^{\frac{1}{2}}(\gamma_-^2-1)^{\frac{1}{2}}\mu]^{\frac{1}{2}}. \quad (5)$$

Equation (5) can be derived from the invariance of the magnitude of the total 4-momentum of the positron-electron system.

We use a Monte-Carlo technique to average equation (4). We choose N triads of uniformly distributed random numbers between 0 and 1, $x_{\mu i}$, x_{+i}, x_{-i}, and we evaluate μ_i, γ_{+i} and γ_{-i} for each triad by solving $\mu_i = 1-2x_{\mu i}$ and the integrals

$$x_{\pm i} = \int_1^{\gamma_{\pm i}} F(\gamma)d\gamma, \quad (6)$$

where $F(\gamma)$ is given by equation (2). We then evaluate γ_i^* and $\sigma^*(\gamma_i^*)$ from equations (3) and (5), and the annihilation rate from

$$R = n_+ n_- N^{-1} \sum_{i=1}^{N} y_i , \tag{7}$$

where

$$y_i = \sigma^*(\gamma_i^*) 2c\beta_i^* \gamma_i^{*2} / (\gamma_{+i}\gamma_{-i}) . \tag{8}$$

The results are shown in Figure 1, based on numerical calculations with $N=5\times10^{8}$. At relativistic temperatures R approaches asymtotically 4×10^{-15} $(kT/mc^2)^{-2}\log(kT/mc^2)$, reflecting the behavior of the annihilation cross section at high energies. In the temperature range 10^8 to 10^9, $R/n_+n_- \approx \pi r_0^2 c$, because the inverse velocity dependence of the nonrelativistic cross section is cancelled by the relative velocity between the particles. At temperatures below 10^8K, R/n_+n_- is taken from the calculations of Crannell et al. (1976) and Bussard et al. (1979). Here the Coulomb attraction between the particles causes the annihilation rate to exceed $\pi r_0^2 c$.

The curve L in figure 1 shows the annihilation luminosity. Since the energy liberated per annihilation is $mc^2(\gamma_+ + \gamma_-)$, L can be evaluated in the same Monte Carlo calculation as R, i.e.

$$L = n_+ n_- mc^2 N^{-1} \sum_{i=1}^{N} (\gamma_{+i} + \gamma_{-i}) y_i . \tag{9}$$

At relativistic temperatures, L also decreases with increasing T, although not as fast as R. For $10^{8} \leq T \leq 10^{9}$, L is approximately constant, because a constant amount of energy, $2mc^2$, is liberated per annihilation. There is a small positive slope in L(T) around 10^9K reflecting an increase in the liberated energy without a substantial decrease in annihilation rate.

The ratio L/2R is the mean photon energy per annihilation. From the numerical calculations we find that for $kT \ll mc^2$, $L/2R \sim mc^2 + \frac{3}{2}\,kT$, i.e. the mean photon energy equals the electron rest mass energy plus the mean particle energy for a nonrelativistic Maxwell-Boltzman distribution. For $kT \gg mc^2$, on the other hand, $L/2R \sim 2kT$, which is less than the mean energy (3kT) for an ultrarelativistic Maxwellian. This is because in the relativistic regime the annihilation rate decreases with increasing energy causing relatively more annihilations of lower energy pairs than of pairs of higher energies. In the nonrelativistic regime, the annihilation rate is energy independent and therefore the mean particle and photon energies are essentially equal.

To evaluate the energy spectrum of the annihilation radiation, a somewhat more complicated approach is needed since it is also necessary to keep track of the individual photon energies resulting from each annihilation. The positron-electron configuration, specified by γ_+,γ_-,μ, only determines the energy of the two photons in the CM frame, $\hbar\omega_1^*=\hbar\omega_2^*=\gamma^* mc^2$. The determination of the photon energies in the frame of the plasma requires that we also specify the directions of the photons. The additional independent variables are $\cos^{-1}\mu^*$ and ϕ^*, the CM angles, respectively, between one of the photons and one of the particles, for example the positron, and between the normals to the planes defined by the positron and the electron and the positron and the gamma ray. The distribution of ϕ^* is uniform, while that of μ^* is determined by the differential cross section in the CM frame (Heitler 1954)

$$\frac{d\sigma^*}{d\mu^*} = \frac{\pi r_0^2}{4} \frac{1}{\gamma^{*2}\beta^*} \left[\frac{\gamma^{*2}+(\gamma^{*2}-1)(2-\mu^{*2})}{(\gamma^{*2}-(\gamma^{*2}-1)\mu^{*2})} - \frac{2(\gamma^{*2}-1)^2(1-\mu^{*2})^2}{(\gamma^{*2}-(\gamma^{*2}-1)\mu^{*2})^2}\right] . \quad (10)$$

The photon energies $\hbar\omega_1$ and $\hbar\omega_2$ in the frame of the plasma can be evaluated as follows: Let $\vec{\beta}_c$ be the velocity of the CM frame, and $\cos^{-1}\mu^*_{\gamma c}$ and $\cos^{-1}\mu^*_{+c}$ be the CM angles between one of the photons and

$\vec{\beta}_c$ and the positron and $\vec{\beta}_c$. In terms of the total energy and momentum of the positron and electron, $E_+ + E_-$ and $\vec{P}_+ + \vec{P}_-$, $\vec{\beta}_c$ and the corresponding Lorentz factor γ_c, can be written as

$$\vec{\beta}_c = c(\vec{P}_+ + \vec{P}_-)/(E_+ + E_-), \tag{11}$$

and

$$\gamma_c = (\gamma_+ + \gamma_-)/(2\gamma^*), \tag{12}$$

where we use equation (5) to derive equation (12) from equation (11). Then $\hbar\omega_1$ and $\hbar\omega_2$ are given by

$$\hbar\omega_{1,2} = mc^2\gamma^*\gamma_c(1 \pm \beta_c\mu^*_{\gamma c}), \tag{13}$$

where

$$\mu^*_{\gamma c} = \mu^*_{+c}\mu^* + (1-\mu^{*2}_{+c})^{1/2}(1-\mu^{*2})^{1/2}\cos\phi^* \tag{14}$$

and

$$\mu^*_{+c} = \frac{\gamma_+ - \gamma_c\gamma^*}{(\gamma_c^2-1)^{1/2}(\gamma^{*2}-1)^{1/2}} \tag{15}$$

Thus, given γ_+, γ_-, μ, μ^* and ϕ^*, we can evaluate the photon energies in the plasma frame by using equations (5), (12), (13), (14) and (15). As a consistency check, we verify energy conservation: from equations (12) and (13) it follows that $\hbar\omega_1+\hbar\omega_2=mc^2(\gamma_++\gamma_-)$.

In the numerical evaluation of the energy spectra we follow a similar procedure as in the evaluation of the annihilation rates. Since we now have 5 independent variables, we choose two additional uniformly distributed random numbers between 0 and 1, x_{μ^*} and x_{ϕ^*}, evaluate γ_{+i}, γ_{-i} and μ_i as in the calculation of R, calculate $\mu_i^*=1-2x_{\mu_i^*}$ and $\phi_i^*=2\pi x_{\phi_i^*}$, and then evaluate the quantity

$$\Delta R(E) = n_+n_-N^{-1}\sum_i[\sigma^*(\gamma_i^*)]^{-1}\,2d\sigma^*/d\mu^*(\gamma_i^*,\mu_i^*)y_i, \tag{16}$$

where y_i is given by equation (8). For a given photon energy, E, the summation is over all values of i for which either $\hbar\omega_{1i}$ or $\hbar\omega_{2i}$, determined from equations (5), (12), (13), (14) and (15), are in the range E to E+ΔE. In the numerical calculations, we choose ΔE sufficiently small to obtain an essentially continuous spectrum.

Numerical results for $N=5\times10^6$ are shown in Figures 2 and 3, where $(2/n_+n_-)\,dR/dE$ is plotted as a function of photon energy for several plasma temperatures from 10^8 to 10^{11} K. As expected, the peak energy of the annihilation line, E_m, and its full width at half maximum, FWHM, increase with T. At temperatures much larger than mc^2, the annihilation spectrum bears no relationship to the characteristic energy 0.511 MeV; instead it is determined by the convolution of the energy spectrum of the e^+-e^- pairs and the annihilation cross section.

By using the numerical results as shown in Figures 2 and 3, and by evaluating annihilation spectra also for a number of other temperatures, we have deduced the dependences of E_m-mc^2 and the FWHM on temperature. We show these in Figure 4. For $kT \ll mc^2$, we can approximate the width by the non-relativistic formula FWHM $\sim$ 11eV$(T(K))^{\frac{1}{2}}$ (e.g., Crannell et al. 1976) and the blueshift by $E_m-mc^2 \sim (3/4)kT$. For $kT \gg mc^2$ both the width and the shift vary linearly with T, in particular $E_m \simeq 1.2kT$. By comparing these results with the mean photon energy discussed above, we see that the peak of the annihilation spectrum is always at a lower energy than its mean, a result caused by the asymmetry of the photon distributions, as can be seen, for example, in Figure 2.

We have repeated the calculations of the present Section using a Fermi-Dirac distribution with zero chemical potential, $F(\gamma) \propto \beta\gamma^2/(e^{\alpha\gamma}+1)$, instead of the Maxwellian given by Equation (2). This distribution describes e^+-e^- pairs in equilibrium with black-body radiation (e.g. Landau and Lifshits 1958). Without considering in detail which distribution might be more appropriate for gamma-ray burst sources, we note here that the two distributions differ appreciably only for $kT \gtrsim mc^2$. Indeed, the annihilation rate turns out to be smaller for the Fermi-Dirac case than for the Maxwell-Boltzman case by only about 1% at 3×10^9K, 8% at 10^{10}K and 15% at 10^{11}K. The blueshifts are also not very different for these temperatures. At 10^{10}K, for example, E_m is larger for the Fermi-Dirac distribution by only about 10% than the E_m for a Maxwellian at the same temperature. As we shall see in the next Section, the temperatures of the annihilation regions of gamma-ray bursts must be quite low ($\lesssim 3\times10^8$K) to produce lines of widths that do not exceed the observations. At these temperatures the differences between the two distributions are essentially negligible.

III. DISCUSSION AND CONCLUSIONS

The results of our calculations could be applied in a straightforward manner to observations of annihilation radiation from optically thin sites. Such sites might be present, for example, in the vicinity of active galaxies, although observations exist only from the Galactic Center where the annihilation site is cooler than 10^5K (Bussard, Ramaty and Drachman 1979).

Gamma ray burst sources are likely to be optically thick. Nevertheless, we can apply our results to their last optical depths, which must be the regions in which the e^+-e^- pairs responsible for the observed emission lines actually annihilate. An upper limit on the temperature of these annihilation sites can be obtained from the observational upper limits on the line widths. For the 400 to 460 keV lines, which we assume to be gravitationally redshifted e^+-e^- annihilation, the full widths at half maximum are less than 200 keV (Teegarden and Cline 1980, Mazets et al. 1981). Then from Figure 4, the temperature of the annihilation region is less than 3×10^8 and hence $E_m - mc^2 < 20$ keV. This shift, about 4%

in the line energy, is significant, since the surface redshifts of neutron stars range from about 5% to 50% depending on their mass and equation of state (Borner and Cohen 1973).

We should note, however, that a blueshift that does not exceed 20keV is actually smaller than the observational uncertainty in the peak energies of the lines (Teegarden and Cline 1980). Also, in the determination of a neutron star parameter, such as mass, the uncertainty caused by a blueshift ranging between 0 and 20keV is of the same order or less than the uncertainty introduced by the poor knowledge of the neutron star equation state (see calculations of Borner and Cohen 1973). Nevertheless, future spectroscopic observations with higher sensitivity could determine the peak energy of the line and its width much more accurately, and these could provide valuable information on neutron star equations of state (see for example Brecher 1977).

The upper limit of 3×10^8K on the temperature of the annihilation region should be compared with the energies of the particles that produce the observed continuum emission of the bursts. Since all gamma ray bursts with observed 400 to 460 keV emission lines have continuum spectra which extend to at least several hundred keV (Mazets et al. 1981, Teegarden and Cline 1980), the radiating particles must have energies of at least these values, i.e. higher by an order of magnitude or more than the kT of the annihilation region. Furthermore, conditions imposed by the pair production threshold, also require particles or photons of energies at least comparable to mc^2 to produce sufficient pairs. Thus, either the positrons annihilate in a spatially distinct region from that responsible for the continuum and the pair production, or the annihilation region is nonthermal.

A spectral feature with peak energy around 430 keV has also been observed from the March 5, 1979 transient (Mazets et al. 1979). The temperature-induced blueshift, discussed in the present paper, was not taken into account in the neutron star vibrational model of this transient proposed by Ramaty et al. (1980). These authors relate the duration of the impulsive spike of the transient to the gravitational redshift by arguing that the duration could equal the damping time of the vibrations. We find here that with an upper limit of 20 keV on the magnitude of the blueshift, and considerable uncertainties in both the energy of the line peak and equation of state, these arguments are not affected by the neglect of the blueshift. Regarding the difference between the radiation and annihilation temperatures, the neutron star vibrational model is expected to produce nonthermal emission, as discussed by Ramaty et al. (1980) and Ramaty, Lingenfelter and Bussard (1981).

As already mentioned in the Introduction, the blueshifting of the e^+-e^- annihilation line in hot plasmas is the consequence of the fact that direct e^+-e^- annihilation proceeds without the formation of an intermediate bound state. On the other hand, a gamma ray line resulting from the deexcitation of a bound nuclear state, for example the line from excited ^{12}C, peaks at 4.44 MeV, independent of the temperature of the plasma. The production of this line in accreting matter around neutron stars and black holes has been considered by Higdon and Lingenfelter (1977). However, in e^+-e^- annihilation, the only available bound state is positronium, and at the high temperatures of interest here, the rate of positronium formation by radiative combination, $e^+ + e^- \rightarrow Ps + \gamma$, is negligible in comparison with direct annihilation $e^+ + e^- \rightarrow \gamma + \gamma$.

Another gamma ray line of considerable astrophysical interest which is formed without an intermediate bound state is the 2.223 MeV line from neutron capture on hydrogen, $n + {}^1H \rightarrow {}^2H + \gamma$ (e.g. Ramaty, Kozlovsky and Lingenfelter 1975). In the 20-minute gamma ray transient of Jacobson et al. (1978), one of the observed lines has been identified with neutron capture on ${}^1H$. As for the 0.511 MeV line, for this line as well, the temperature-induced blueshift is of the order kT. We defer a more detailed evaluation of this shift and its astrophysical consequence to another paper.

In conclusion, we have pointed out a hitherto ignored effect in astrophysical applications, the blueshifting of the e^+-e^- annihilation line due to the temperature of the annihilation region. We have evaluated in detail the annihilation rate and annihilation spectrum of a hot e^+-e^- plasma. By applying our results to gamma ray bursts, we find that the temperature of the annihilation region in burst sources is less than about 3×10^8K, that the temperature-induced blueshift of the 0.511 MeV line is less than 20 keV, and that either the annihilation region is nonthermal or spatially distinct from the burst site itself.

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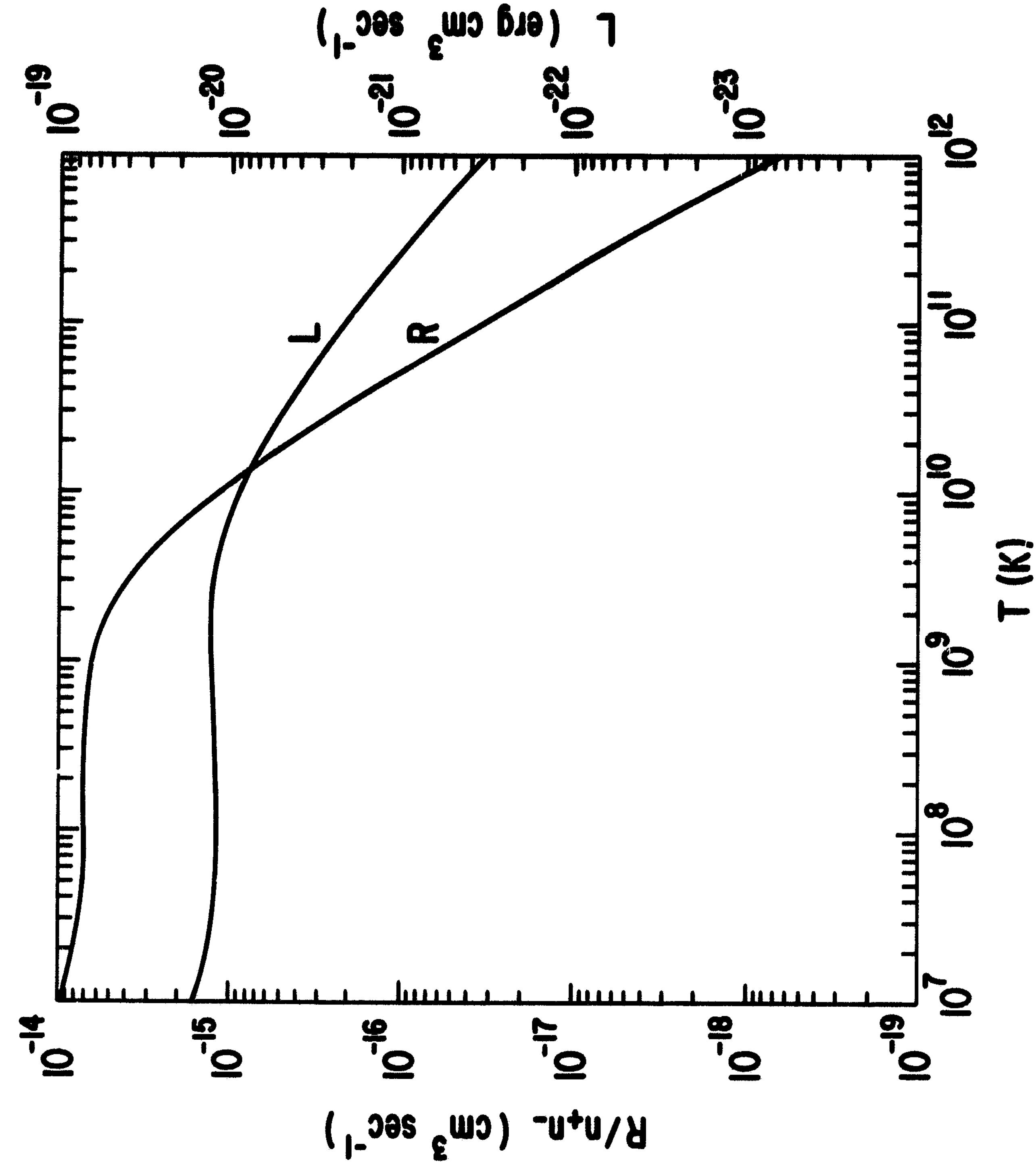
FIGURE CAPTIONS

1. Annihilation rate, R, and annihilation luminosity, L, of an e^+-e^- plasma as functions of temperature.

2. Annihilation spectra for various temperatures.

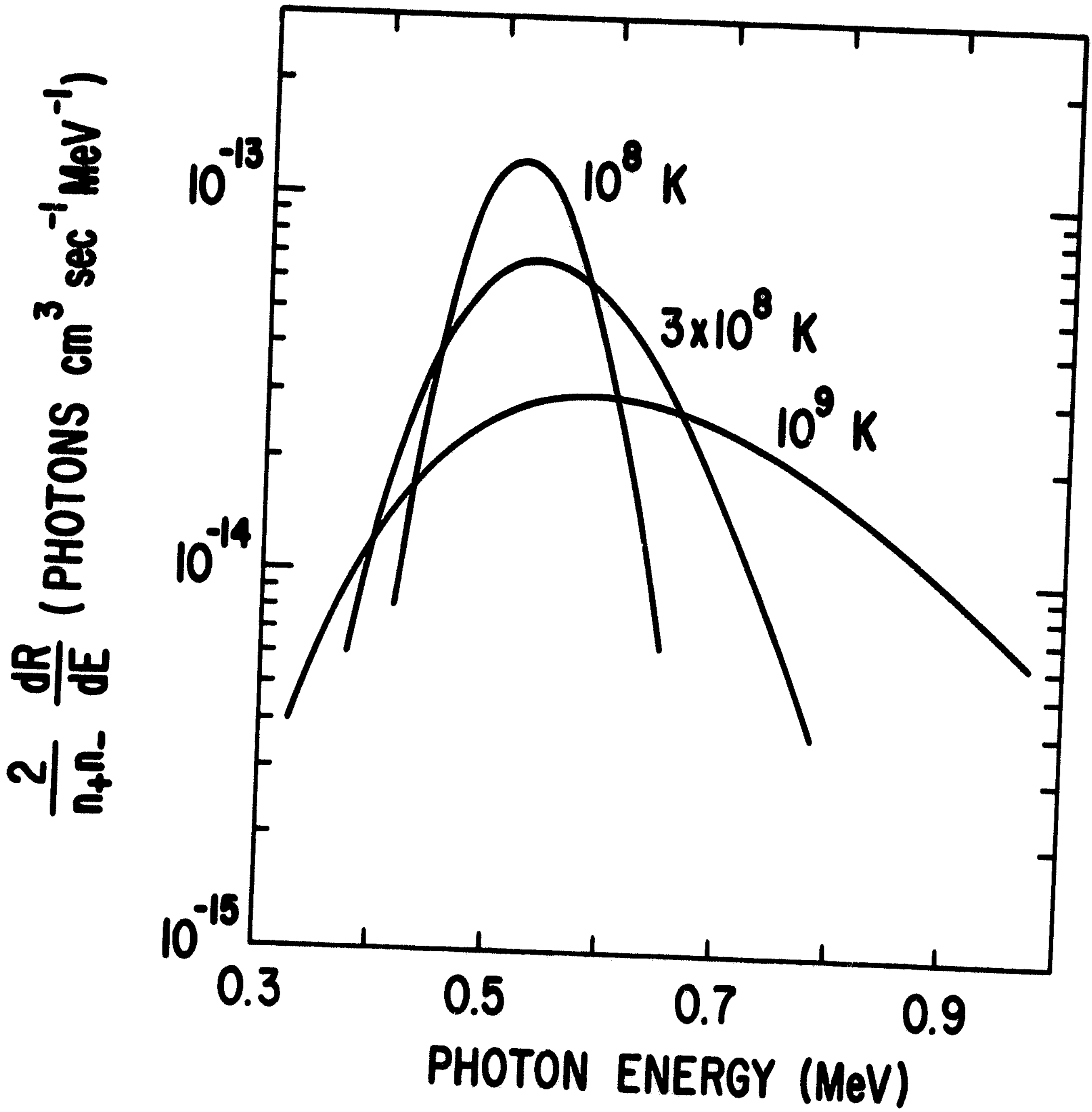
3. Annihilation spectra for various temperatures.

4. Temperature-induced blueshift, E_m-mc^2, and full width at half maximum, FWHM, of the e^+-e^- annihilation feature as function of temperature.



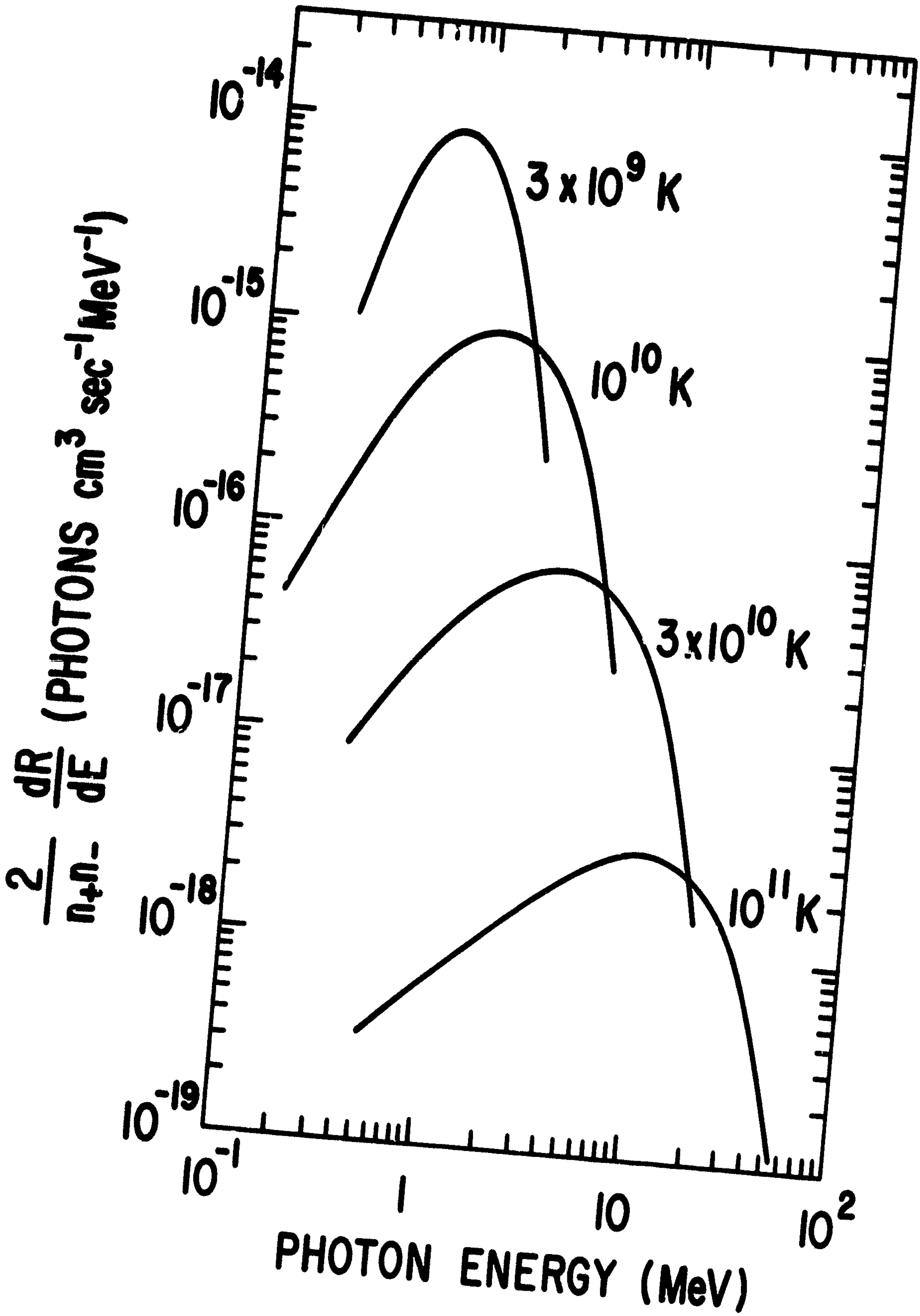
L (erg cm3 sec-1)
R/n+n- (cm3 sec-1)
T (K)
L
R
10-14
10-15
10-16
10-17
10-18
10-19
10-19
10-20
10-21
10-22
10-23
107
108
109
1010
1011
1012

fig. 1



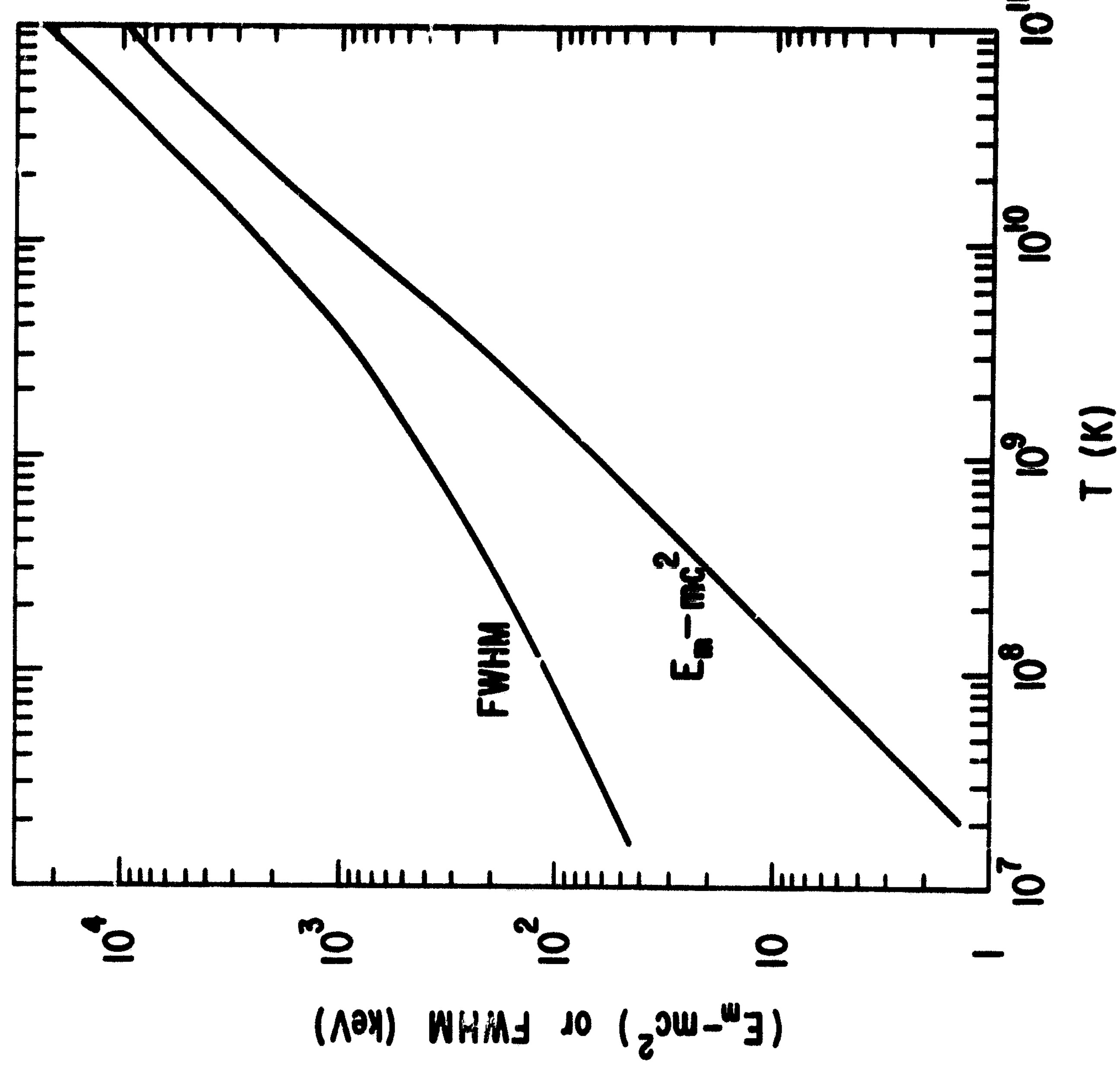
$\frac{2}{n_+ n_-} \frac{dR}{dE}$ (PHOTONS cm^3 sec^{-1} MeV^{-1})
10^{-13}
10^{-14}
10^{-15}
10^8 K
3×10^8 K
10^9 K
0.3
0.5
0.7
0.9
PHOTON ENERGY (MeV)

fig. 2



$\frac{2}{n_+ n_-} \frac{dR}{dE}$ (PHOTONS cm^3 sec^{-1} MeV^{-1})
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
3×10^9 K
10^{10} K
3×10^{10} K
10^{11} K
10^{-1}
1
10
10^2
PHOTON ENERGY (MeV)

fig. 3



FWHM
E_m − mc²
T (K)
(E_m−mc²) or FWHM (keV)
10⁷
10⁸
10⁹
10¹⁰
10¹¹
1
10
10²
10³
10⁴

fig. 4