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THE COSMIC γ-RAY BACKGROUND FROM THE ANNIHILATION OF PRIMORDIAL STABLE NEUTRAL HEAVY LEPTONS

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ABSTRACT

In light of the recent work on the astrophysical implications of the possible existence of stable neutral heavy leptons and the suggestion that continuing annihilation of heavy leptons produced in the big bang might produce a substantial cosmic γ-ray background radiation, we examine in detail the spectra and intensities of such radiation from (1) a homogeneous cosmic lepton background, (2) a possible lepton halo around the Galaxy, and (3) integrated background radiation from possible lepton halos around other galaxies and from rich galaxy clusters. In the case of our own galactic halo, γ-radiation from heavy-lepton annihilation appears to be able to account for the intensity of the observed background only if there are ~ 100 γ-rays produced per annihilation. However, in that case both the energy spectrum and isotropy would be inconsistent with the observations. More likely lepton annihilation fluxes from a galactic halo would be confused with cosmic-ray–produced radiation and therefore would be difficult to observe. Heavy-lepton annihilation radiation from the halos of other galaxies accounts for at most 5×10^{-3} of the background intensity, and those from rich clusters account for at most 5×10^{-5} of the background intensity. Those from a homogeneous cosmological lepton background appear to be able to account for $\lesssim 10^{-4}$ of the observed cosmic γ-ray background, although the spectrum and isotropy in this case would be consistent with the data.

Subject headings: cosmic rays: general — cosmology — elementary particles — gamma rays: general

I. INTRODUCTION

Lee and Weinberg (1977*b*) have recently discussed the possibility that large numbers of stable neutral heavy leptons (L^0) and antileptons ($\bar{L}^0$) may exist in the universe as remnants of the big bang. These leptons may even provide enough mass to gravitationally close the universe. Such neutral heavy leptons may exist as a consequence of an extended gauge theory of weak and electromagnetic interactions (Lee and Weinberg 1977*a*). Sequential heavy leptons (i.e., those with new conserved quantum numbers), where the neutral is of lower mass than the charged lepton, will be stable (Perl and Rapidis 1974). Other astrophysical consequences of the possible existence of remnant $L^0\bar{L}^0$ pairs are starting to be investigated (Dicus, Kolb, and Teplitz 1977; Gunn *et al.* 1978; Steigman, 1977). In particular, it has been suggested (Gunn *et al.* 1978; Steigman 1977) that if $L^0\bar{L}^0$ annihilation provides an observable or dominant part of the cosmic γ-ray background, the γ-ray observations could be used to test for the properties of neutral heavy leptons. We will undertake here a detailed examination of the cosmic γ-ray background to be expected from $L^0\bar{L}^0$ annihilation, based in part on previous calculations (Stecker, 1967, 1971, 1977*a*; Stecker, Morgan, and Bredekamp 1971). We further show that it is unlikely that this process will provide a significant contribution to the cosmic γ-ray background.

II. HEAVY-LEPTON DENSITIES

As a starting point, we note that Lee and Weinberg (1977*b*) have calculated the amount of matter in the form of neutral heavy leptons and antileptons as a function of the L^0 mass M_L and obtain the approximate relation

$$\rho_L \approx 8.4 \times 10^{-28} N_A^{-0.95} M_L(\mathrm{GeV})^{-1.85}\ \mathrm{g\ cm^{-3}}, \quad (1)$$

where $N_A = 14$ corresponds to the number of annihilation channels open for $M_L \sim 2$ GeV ($L^0\bar{L}^0 \to \nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$, e^-e^+, $\mu^-\mu^+$, and $u_i\bar{u}_i$, $d_i\bar{d}_i$, $s_i\bar{s}_i$ counted for each of three colors i).[1] We will also consider the possibilities $M_L = 5$ and 10 GeV and allow four other channels $L^0\bar{L}^0 \to \tau\bar{\tau}$, $c_i\bar{c}_i (i = 1, 2, 3)$, so that for these cases, $N_A = 18$. The corresponding number density of neutral heavy leptons and antileptons is

$$n_L \equiv n_{L^0} = n_{\bar{L}^0} = \rho_L/2M_L\,. \quad (2)$$

In the three cases we will consider, $M_L = 2$, 5 and 10 GeV, equations (1) and (2) yield the results shown in Table 1.

The case $M_L = 2$ GeV corresponds to the upper limit on the density of the universe $\rho_L \approx 2\ 10^{-29}$ g

[1] Here u, d, s, and c are the *up*, *down*, *strange*, and *charmed* quarks, τ is the newly discovered τ-lepton, and ν_τ is its corresponding neutrino.

TABLE 1

RELEVANT L^0 DENSITIES

M_L (GeV)	ρ_L (g cm^{-3})	n_L (cm^{-3})
2	1.9×10^{-29}	2.7×10^{-6}
5	2.8×10^{-30}	1.5×10^{-7}
10	1.9×10^{-30}*	5.2×10^{-8}*

* In the case $M_L = 10$ GeV, the density is higher than that given by equation (1) by a factor of ~ 2.46 (Lee and Weinberg 1977*b*).

cm^{-3} (Lee and Weinberg 1977*b*). Values of M_L below 2 GeV are ruled out by the cosmological data unless $M_L \lesssim 40$ eV. Thus, the τ-neutrino, with mass $M_\tau \lesssim 0.6$ GeV (Perl *et al.* 1977) cannot be regarded as relevant in this context. A value for M_L between 5 GeV and 10 GeV corresponding to a gravitationally open universe will yield a steeper γ-ray spectrum for $E_\gamma > 35$ MeV. For an open universe $I_A(E_\gamma) \sim E_\gamma^{-3}$, whereas for a closed universe $I_A(E_\gamma) \sim E_\gamma^{-2.5}$ (Stecker 1971; see also § IV) for 35 MeV $\lesssim E \sim 150$ MeV. Observationally, in this energy range, $I_{\rm obs}(E_\gamma) \sim E_\gamma^{-\Gamma}$, where $\Gamma = 2.85(+0.5, -0.35)$ (Fichtel, Simpson, and Thompson 1978).

III. ANNIHILATION RATE

The annihilation cross section for nonrelativistic neutral heavy leptons (L^0's) is given by

$$\sigma_A = \frac{G_F{}^2 M_L{}^2 N_A}{2\pi v_L}\,, \tag{3}$$

where $G_F = 1.5 \times 10^{-5}\,\text{GeV}^{-2}$ and M_L is again in GeV, and v_L is the velocity of the lepton (Lee and Weinberg, 1977*b*). The annihilation rate per unit volume is then

$$\begin{aligned}\psi_A &= \sigma_A v_L n_{L^0} n_{\bar{L}^0} \\ &= 3.42 \times 10^{-27} M_L{}^2 \left(\frac{N_A}{14}\right) n_L{}^2\ \text{cm}^{-3}\ \text{s}^{-1}\,. \end{aligned} \tag{4}$$

The γ-ray production rate per unit volume is then

$$q_\gamma = \zeta_\gamma (N_H/N_A)\psi_A\,, \tag{5}$$

where ζ_γ is the mean number of γ-rays (γ-ray multiplicity) produced by meson decay in the hadronic annihilation channels (those involving quark pair production) and N_H is the number of open hadronic annihilation channels. For $M_L = 2$ GeV we take $N_H = 9$ corresponding to the $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ channels; and for $M_L = 5$ and 10 GeV we take $N_H = 12$, taking account of the additional $c\bar{c}$ channels. Thus the ratio $R_H = N_H/N_A$ will be either ~ 0.64 or ~ 0.67. The leptonic channels do not contribute to γ-ray production.

We will further assume that ζ_γ and the mean ζ-ray energy $\bar{E}_\gamma$ resulting from each meson produced is determined by a statistical thermodynamic model (see, e.g., Nikitin and Rozental' 1976). We will start from the statistical model of Matsuda (1966) which has been very successful in determining these parameters in $p\bar{p}$ annihilation (Stecker 1967, 1971).

One conclusion from this model is that only the π^0 mesons produced in the annihilation contribute significantly to γ-ray production (Stecker 1967, 1971). The π^0 mesons produce γ-rays through the decay $\pi^0 \rightarrow 2\gamma$ for which the branching ratio is $\sim 100\%$. The heavier mesons are produced in much smaller quantities in thermodynamic equilibrium. In the case of $p\bar{p}$ annihilation, the number of π^0 mesons produced, ζ_{π^0}, is given by

$$\zeta_{\pi^0}{}^{p\bar{p}} = [\exp \beta_p(\bar{E}_\pi - \mu_\pi) - 1]^{-1}\,, \tag{6}$$

where $\beta_p{}^{-1} = 0.15$ GeV and $\mu_\pi = 0.295$ GeV. The quantity β^{-1} represents an effective temperature.

We will assume that, in the case of $L^0\bar{L}^0$ annihilations taking place at low energies, the effective thermalization volume $V_{\rm th}$ is initially of order

$$V_{\rm th} \sim M_L{}^{-3}\,. \tag{7}$$

(There is no Lorentz contraction factor as in the case of multiple production in high-energy $p\bar{p}$ collisions.)

The total energy available in the annihilation is $W = 2M_L$. The energy density is therefore

$$\epsilon = \text{const.} \times T^4 = \frac{W}{V_{\rm th}} \sim M_L{}^4\,, \quad \text{or} \quad T \sim M_L\,, \tag{8}$$

from which we obtain the relation

$$\beta_L = (M_p/M_L)\beta_p\,. \tag{9}$$

The number density of particles formed in thermal equilibrium $n_\pi \sim T^3$ so that the pion multiplicity

$$\zeta_{\pi^0} = n_{\pi^0} V_{\rm th} \sim T^3/M_L{}^3 = \text{const.} = 1.32\,. \tag{10}$$

Substituting relations (9) and (10) into equation (6), we can then calculate the average π^0 energy $\bar{E}_\pi$ for various values of M_L. The results are shown in Table 2 under the heading of Model I.

TABLE 2

CALCULATED γ-RAY MULTIPLICITIES AND MEAN ENERGIES

Annihilation Process	$\zeta_\gamma = 2\zeta_\pi$	$\bar{E}_\gamma \equiv E_m = \bar{E}_\pi/2$ (GeV)
$p\bar{p}$	2.64	0.19
$L^0\bar{L}^0$:		
$M_L = 2$ GeV:		
I	2.64	0.24
II	4.7	0.18
III	3.9	0.28
$M_L = 5$ GeV:		
I	2.64	0.37
II	9.3	0.17
III	6.0	0.44
$M_L = 10$ GeV:		
I	2.64	0.60
II	15.6	0.16
III	8.6	0.62

Alternatively, we can consider another possibility that thermalization ultimately takes place over a volume

$$V_{\rm th} \sim m_\pi^{-3}\,, \tag{7a}$$

independent of M_L. In that case

$$\beta_L = (M_p/M_L)^{1/4}\beta_p \tag{9a}$$

and

$$\zeta_{\pi^0} \sim T^3 = 1.32(M_L/M_p)^{3/4}\,. \tag{10a}$$

In this alternate case, we use relations (9a) and (10a) in equation (6), and these results are listed as Model II.

As a final alternative we consider a "maximal" case for γ-ray production as Model III. Noting that in Models I and II the fraction of energy going into γ-rays, viz., $\zeta_{\pi^0}\bar{E}_{\pi^0}/2M_L$, decreases with M_L, we consider a model where $\zeta_{\pi^0}\bar{E}_{\pi^0}/2M$ = const., taken to be the value found in $p\bar{p}$ annihilation:

$$\xi_\gamma = \frac{\zeta_{\pi^0}{}^{L\bar{L}}\bar{E}_{\pi^0}{}^{L\bar{L}}}{2M_L} = \frac{\zeta_{\pi^0}{}^{p\bar{p}}\bar{E}_{\pi^0}{}^{p\bar{p}}}{2M_p}\,. \tag{11}$$

We further assume in Model III that both ζ_π and E_π scale as $M_L^{1/2}$, an intermediate case between the dependencies of these quantities on M_L in Models I and II. Thus, Model III should take account of any extra energy going into γ-rays which Models I and II may not have accounted for—e.g., π^0-mesons produced from the decay of higher-mass secondaries or an increase in mean energy carried off by one or two secondaries not totally in thermal equilibrium. Results for Model III are also given in Table 2.

IV. SPECTRAL SHAPE

In the case of Model II, the mean π^0 energy E_m is almost independent of M_L. In this case, the γ-ray spectrum from $L^0\bar{L}^0$ annihilation for M_L of a few GeV may be quite similar to that calculated from the statistical model for $p\bar{p}$ annihilation (Stecker 1967, 1971) which fits the laboratory data quite well. This spectrum is shown in Figure 1.

For our purposes, we may simplify our calculation by approximating statistical spectra, such as that shown in Figure 1, by a normalized spectrum of the form

$$f(E_\gamma) = E_m^{-1}\exp(-E/E_m)\,. \tag{12}$$

The real differential γ-ray spectrum will always have a maximum at $E_\gamma = m_\pi/2 \approx 0.07$ GeV. The effect of a higher E_m, corresponding to a higher effective temperature, is to spread out the spectrum over a wider energy range (Stecker 1971).

The Cosmic background spectrum for $E_\gamma \lesssim E_m$ is then given by the equation (Stecker 1971)

$$I(E_\gamma) = \frac{c}{4\pi H_0}q_\gamma{}^0\phi(E_\gamma)\,, \tag{13}$$

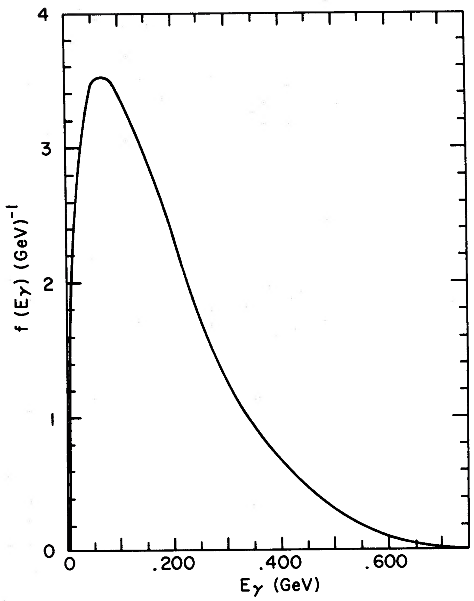

FIG. 1.—The calculated γ-ray spectrum from $p\bar{p}$ annihilation (Stecker 1967, 1971).

where

$$\phi(E_\gamma) = \int_0^{z_c} dz\,\frac{(1+z)^2}{(1+\Omega z)^{1/2}}f[(1+z)E_\gamma]\,, \tag{14}$$

$q_\gamma{}^0$ is the present γ-ray production rate per unit volume, H_0 is the Hubble constant (taken to be 2×10^{-18} s^{-1}), z is redshift, and $\Omega = 8\pi G\rho/3H_0{}^2$, ρ being the mean density of the universe. The limit z_c, the critical redshift for absorption from pair production interactions, is in the range $100 \lesssim z_c \lesssim 200$ (Stecker 1975). A proper treatment for $E_\gamma \lesssim E_m/z_c$ is given by Stecker, Morgan, and Bredekamp (1971).

Again for simplicity we consider the open universe case $\Omega z \ll 1$. (Taking $\Omega = 1$ will make only a small difference in our estimates of the γ-ray background intensity above 0.1 GeV; however, as previously noted, it does change the exponent of the calculated power-law energy spectrum from -3 to -2.5.)

Substituting $f(E_\gamma)$ from equation (12) into equation (14), we then obtain

$$\phi(E_\gamma) \approx E_m{}^2E_\gamma{}^{-3}(1 + E_\gamma/E_m)^2\exp(-E_\gamma/E_m) \approx E_m{}^2E_\gamma{}^{-3} \tag{15}$$

for $E_\gamma \lesssim E_m/3$.

The γ-ray intensity above an energy E_γ is then given by

$$I(>E_\gamma) = \frac{cq_\gamma{}^0}{4\pi H_0}\int_{E_\gamma}^\infty dE_\gamma\phi(E_\gamma) = \frac{cq_\gamma{}^0}{4\pi H_0}\kappa_\gamma(E_\gamma|E_m)\,, \tag{16}$$

where

$$\kappa_\gamma(E_\gamma|E_m) = \tfrac{1}{2}(E_m/E_\gamma)^2 \tag{17}$$

for γ-rays above 0.1 GeV:

$$\kappa_\gamma(>0.1|E_m) = 50E_m{}^2\,(\text{GeV})\,. \qquad (18)$$

The cosmic γ-ray background intensity above 0.1 GeV is then found from equations (4), (5), (16), and (18), and is given by

$$I_\gamma(>0.1) = 14.5 N_H M_L{}^2 E_m{}^2 \zeta_\gamma n_L{}^2\,, \qquad (19)$$

with n_L given in Table 1 and with $N_H = 9$ for $M_L = 2$ GeV, and $N_H = 12$ for $M_d = 5$ and 10 GeV.

Table 3 shows the values for the cosmic γ-ray background intensity calculated from equation (19). We also show, for comparison, the measured value of the cosmic γ-ray background above 0.1 GeV (Fichtel, Simpson, and Thompson 1978).

It can be immediately seen from Table 3 that even in the best case allowed by the cosmological data ($M_L \approx 2$ GeV) and under the most optimistic assumptions regarding γ-ray production in $L^0\bar{L}^0$ annihilation (Case III), the calculated background is $\lesssim 10^{-4}$ of the observed cosmic γ-ray background flux. Therefore, even though the $L^0\bar{L}^0$ annihilation process gives a spectrum which is similar in shape to the measured background, since it is similar in shape to that calculated from $p\bar{p}$ annihilation (cf. Stecker 1977*a*, *b*, 1978), the intensity of the background cannot be explained by this process.

V. ANNIHILATION γ-RAYS FROM A HEAVY-LEPTON GALACTIC HALO

It has also been suggested that γ-rays from an $L^0\bar{L}^0$ halo around our Galaxy might be detectable. These γ-rays could have a spectrum similar to that shown in Figure 1.

The lepton density calculated for the Galaxy is given by Gunn *et al.* (1978) as

$$n_L \approx \frac{n_0 a^2}{M_L(r^2 + a^2)} \qquad (20)$$

where $n_0 = 0.14\ \text{cm}^{-3}$, r is galactocentric distance, and $a \approx 3 \times 10^{22}$ cm. The γ-ray intensity above 100 MeV from the lepton halo would then be of the order

$$I_\gamma{}^{LL}(\text{halo}) \sim \frac{q_\gamma a n_0{}^2}{4\pi M_L{}^2} \sim 10^{-7}\zeta_\gamma\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,. \qquad (21)$$

Thus, the calculated flux from the galactic halo is expected to be of the order of the observed background only if $\zeta_\gamma \sim 100$. In that case, the spectrum of the radiation would be much harder than that observed for $E_\gamma \sim 0.1$ GeV. Also, Fichtel, Simpson, and Thompson (1978) conclude that a γ-ray halo of size $\lesssim 40$ kpc ($\sim 10^{23}$ cm) is inconsistent with their determination of the isotropy of the cosmic γ-ray background radiation. Thus, $L\bar{L}$ annihilation probably can make up at most about one-third of the background, and therefore $\zeta_\gamma \lesssim 30$. (For Model II this places an upper limit of ~ 25 GeV on M_L; however, in the case of Model I no upper limit on M_L is implied.)

In the more likely case that halo lepton annihilation radiation produces at most a few percent of the background, such radiation would be observationally confused with cosmic-ray–produced radiation both in the galactic disk at high latitudes and in a cosmic-ray halo. In particular, Compton effect γ-radiation may overpower that from lepton annihilation while π^0-decay radiation from cosmic-ray nuclei interacting with diffuse halo gas as well as high-latitude disk gas would be confused with lepton annihilation radiation because of its similar energy spectrum (Stecker 1971, 1977*a*). If the cosmic-ray halo in our Galaxy forms a considerably flattened system (Stecker and Jones 1977), it may be possible in principle to detect a lepton-annihilation halo by looking for a weak spherical emissivity distribution centered around the galactic center with a spectrum in the energy range between 0.07 and 0.3 GeV which is flatter than an E^{-2} Compton produced spectrum. However, in practice the feasibility of such a test is questionable.

VI. OTHER GALACTIC HALOS AND GALAXY CLUSTERS

The contribution to the γ-ray background radiation from possible $L^0\bar{L}^0$ halos of other galaxies can also be estimated as

$$I_\gamma{}^{LL}(\text{galaxies}) \sim \frac{n_{\text{gal}} q_{\gamma,\text{gal}} V_{\text{gal}}}{4\pi(H_0/c)} \sim 1.8 \times 10^{-9}\zeta_\gamma\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,, \qquad (22)$$

where $n_{\text{gal}} \sim 3 \times 10^{-76}\ \text{cm}^{-3}$ is the number density of galaxies,[2] $V_{\text{gal}} \sim 10^{68}\ \text{cm}^3$ is taken to be the mean volume of the $L^0\bar{L}^0$ halo, and $\bar{q}_{\gamma,\text{gal}}$ is estimated from equations (4), (5), and (20) to be $\sim 4 \times 10^{-29}\zeta_\gamma$ $\text{cm}^{-3}\,\text{s}^{-1}$. Taking $\zeta_\gamma \lesssim 30$ (see § V), we conclude that $L^0\bar{L}^0$ annihilation in other galactic halos accounts for at most $\sim 5 \times 10^{-3}$ of the background.

TABLE 3

COSMIC γ-RAY BACKGROUND INTENSITIES ABOVE 100 MeV

Model	Intensity ($\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$)
$M_L = 2$ GeV:	
I	5.3×10^{-10}
II	5.8×10^{-10}
III	1.2×10^{-9}
$M_L = 5$ GeV:	
I	3.7×10^{-11}
II	2.8×10^{-11}
III	1.2×10^{-10}
$M_L = 10$ GeV:	
I	4.6×10^{-11}
II	1.9×10^{-11}
III	1.6×10^{-10}
Observed (Fichtel *et al.* 1978)	$0.9 \pm 0.2 \times 10^{-5}$

[2] Felten (1977 and private communication). This is for galaxies down to a luminosity 5 times fainter than our own Galaxy and 10 times fainter than the "knee" in the galaxy luminosity function.

By solving an equation similar to equation (22) for rich clusters of galaxies, one can estimate the contribution to the γ-ray background from the annihilation of L^0's in rich clusters. For the Coma cluster, Gunn *et al.* find that, for all the missing mass in L^0's and $\bar{L}^0$'s, $a \sim 100$ kpc and the central density is $\sim 5 \times 10^{-2} M_L^{-1}$ cm^{-3}. Assuming a mean density of rich clusters in the universe of 2×10^{-80} cm^{-3} (5.5×10^{-7} Mpc^{-3}, Abell 1976) and again assuming $\zeta_\gamma \lesssim 30$, we find

$$I_\gamma^{LL}(\text{clusters}) \sim \frac{n_{\text{cl}} q_{\gamma,\text{cl}} V_{\text{cl}}}{4\pi(H_0/c)} \lesssim 4.5 \times 10^{-10}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ . \tag{23}$$

Thus, the contribution from annihilation in rich clusters amounts to $\lesssim 5 \times 10^{-5}$ of the observed background.

VII. CONCLUSIONS

Data on the isotropy and energy spectrum of high galactic latitude γ-radiation indicates that if our Galaxy has a halo of heavy leptons of the type suggested by Gunn *et al.* (1977), annihilation radiation from this halo can make up, at most, about one-third of the observed intensity. This places an upper limit of ~ 30 γ-rays per annihilation on such radiation. Such an upper limit implies that the halos of other galaxies can contribute a component of annihilation radiation accounting for at most $\sim 5 \times 10^{-3}$ of the observed background. Halo lepton annihilation radiation from our Galaxy will, most probably, be observationally confused with high-latitude cosmic-ray–produced radiation and thus would be difficult to observe.

Cosmological annihilation radiation from heavy leptons has the proper spectral shape and isotropy to account for the observations. However, even in our "best case" as shown in Table 3, such radiation accounts for only about 10^{-4} of the observed background. Table 3 also shows that the "best case" corresponds to the smallest possible value of M_L and that going to higher values of M_L lowers the predicted background intensity. The best case predictions for large values of M_L correspond to producing a few γ-rays of large E_m where $E_m \sim M_L$ (probably unphysical, but the highest possible M_L dependence for E_m). In this limit, we must consider that $\Omega z \gg 1$ for γ-rays of energy in the 0.1 GeV range. This implies, from equation (14), that $\kappa \sim E_m^{3/2}$. Also in this case $\zeta_\gamma = $ const. It then follows from equations (1), (2) and (19) that $I(>E_\gamma) \sim M_L^{-2.2}$. There is an additional increase in the predicted intensity $\sim N_F^{0.95}$, where N_F is the number of degrees of freedom in the early blackbody radiation; however, this increase cannot make up for the $M_L^{-2.2}$ dependence. Also, for $E_m > 0.1 z_c$, κ no longer increases with E_m. For $M_L \gtrsim M_W$ (assumed to be ~ 40 GeV) where M_W is the mass of the intermediate vector boson, $\sigma_A v$ no longer increases as M_L^2 and $I(>E_\gamma) \sim M_L^{-5.7}$. Thus, higher mass leptons would only provide much smaller amounts of annihilation radiation to the γ-ray background.

Thus, we conclude that, whereas there might be enough mass in heavy neutral leptons to account for the missing mass in galaxies and galaxy clusters and to close the universe, annihilation radiation from these leptons will not constitute a readily observable contribution to the γ-ray background radiation. It appears that nucleon annihilation radiation in a baryon-symmetric big bang cosmology remains the most promising proposed mechanism for explaining both the energy spectrum and the intensity of the observed cosmic γ-ray background (Stecker 1977*a*, *b*, 1978; Fichtel, Simpson, and Thompson 1978).

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