J. Phys. G: Nucl. Part. Phys. **17** (1991) 1769–1778. Printed in the UK

Cosmic ray positrons connected with galactic gamma radiation of high and very high energies

F A Aharonian and A M Atoyan
Yerevan Physics Institute, 375036 Yerevan, Alikhanian Brothers Str. 2, Armenia, USSR

Received 4 December 1990, in final form 2 April 1991

Abstract. A model of high-energy positrons in cosmic rays is suggested according to which the positron flux detected at $E \geqslant 10\,\mathrm{GeV}$ is due to the interactions of very high energy ($E_\gamma > 100\,\mathrm{GeV}$) gamma rays with optical and ultraviolet (UV) radiation in the vicinity of discrete sources. In the frames of the model it is possible to explain both the sharp increase of the ratio $r_+(E) = e^+/(e^+ + e^-)$ in cosmic rays at energies $E \geqslant 10\,\mathrm{GeV}$, and the total spectra of electrons and positrons at energies $E \leqslant 1\,\mathrm{TeV}$.

1. Introduction

In a number of recent independent experiments (Buffington *et al* 1975, Müller and Tang 1985, Golden *et al* 1987) a sharp increase of the content of positrons in cosmic rays (CR) at energies $E \geqslant 10\,\mathrm{GeV}$ has been observed. Such a behaviour of $r_+(E) \equiv e^+/(e^- + e^+)$ is not explained in frames of standard models assuming the secondary origin of positrons (due to interactions of CR with interstellar medium), while at lower energies, $E = 1\,\mathrm{GeV}$, the positron flux predicted by these models is consistent with the measured flux of positrons (see, e.g., Protheroe 1982, Müller and Tang 1990). Presumably, new ideas and approaches are needed to interpret this effect.

What are the questions to be answered?

(i) The positron flux at energies $E \geqslant 10\,\mathrm{GeV}$ arises suddenly; at least the ratio $r_+ = e^+/(e^- + e^+)$ increases up to $r_+ = 0.2$ at $E = 14 \div 20\,\mathrm{GeV}$, being $r_+ \leqslant 0.05$ at $E \simeq 3\,\mathrm{GeV}$ (Müller and Tang 1985).

(ii) A sharp increase of the flux of the new component of positrons further should at least slow down and even decrease so as not to contradict the absolute flux of CR electrons (e^- and e^+) at $E \simeq 1\,\mathrm{TeV}$. In particular, such a contradiction may arise in the model of Harding and Ramaty (1987), where the e^+e^- production in pulsars is discussed, if the cut-off in the e^+e^- spectrum of a pulsar at $E \simeq 1\,\mathrm{TeV}$ is not supposed. So any model should provide an unusual spectrum of the new component of the positrons, with an increase up to $E \sim 10\,\mathrm{GeV}$, reaching a plateau, and finally decreasing above several tens of GeV.

In the present paper we propose a model which makes it possible to understand and explain the observed peculiarities of both the ratio $r_+(E)$ and the total electron spectrum. The basic idea of the model consists of the assumption that the positron flux detected at $E \geqslant 10\,\mathrm{GeV}$ is due to the interactions of the high energy gamma rays with the ambient low-frequency photons in the vicinity of discrete sources. The large

0954-3899/91/111769 + 10 \$03.50

cross section of e^+e^- pair production at photon–photon interactions ($\sigma_{\gamma\gamma} \sim 10^{-25}\,\mathrm{cm}^2$) can provide a high efficiency of positron production in the vicinity of gamma-ray sources where high densities of low-frequency radiation are possible. Besides the high positron production rate, this mechanism also leads to a peculiar spectrum of secondary electrons due to the kinematics of the reaction $\gamma\gamma \rightarrow e^+e^-$.

The energy E_γ of the gamma rays interacting with the ambient isotropically distributed photons with characteristic energy ε_0 must exceed the threshold value, $E_\gamma \geqslant E_{\mathrm{th}} = (m_e c^2)^2/\varepsilon_0$. Since one of the secondary electrons takes almost the whole energy of the gamma quantum, and as we are interested in the electron energy range $10 \leqslant E \leqslant 100$ GeV, obviously the gamma rays in the energy range $10\,\mathrm{GeV} \leqslant E \leqslant 1$ TeV will be considered. These gamma rays interact most efficiently with the optical and UV photons $1 < \varepsilon_0 < 100$ eV, since the cross section $\sigma_{\gamma\gamma}(E_\gamma, \varepsilon_0)$ reaches the maximum at $E_\gamma \varepsilon_0/(m_e c^2)^2 \simeq 3$.

In principle, the gamma rays may interact with optical photons both near the source and in the interstellar medium. The analysis shows that to explain the observed fluxes of positrons at $E \geqslant 10$ GeV in frames of the model proposed, the gamma-ray interaction probability should be $\tau_{\gamma\gamma} \geqslant 0.1$ (see below). Such high probabilities cannot be reached for interactions of gamma rays with starlight in the interstellar medium, as in this case $\tau_{\gamma\gamma} = \bar{\sigma}_{\gamma\gamma} n_{\mathrm{opt}} d$ is only $\tau_{\gamma\gamma} \sim 10^{-4}$ ($d \sim 300$ pc and $n_{\mathrm{opt}} \sim 1\,\mathrm{cm}^{-3}$ being the thickness of the galactic disc and the starlight number density in the interstellar medium, respectively). So, the high values of $\tau_{\gamma\gamma}$ required may be provided only for interactions of the gamma rays in the near vicinity of relatively compact gamma-ray sources.

2. The total gamma-ray flux from discrete sources in the galactic disc

The basic parameter for calculation of the high-energy positron flux in frames of the model proposed is the gamma-ray luminosity of the galaxy provided by discrete sources. Unfortunately, the energy range of gamma rays of interest, $10\,\mathrm{GeV} \leqslant E \leqslant 1$ TeV, is quite uncertain. Nevertheless, below we can use reasonable estimates for the relevant gamma-ray fluxes, by extrapolating the fluxes available at $E_\gamma \geqslant 100$ MeV to higher energies, and not contradicting data at very high ($E \geqslant 1$ TeV) and ultra-high ($E > 10^{14}$ eV) energies.

The observed COS B intensity of the galactic disc at $E_\gamma \geqslant 100$ MeV within $|b| \leqslant 10°$, averaged over all galactic longitudes, is $J_\gamma(\geqslant 100\,\mathrm{MeV}) = 2 \times 10^{-4}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ (Vladimirsky 1988). This flux consists of two components: the truly diffuse component connected with the processes in the interstellar medium, and the component owing to superposition of gamma radiation from unresolved discrete sources. At $E_\gamma \sim 100$ MeV, the contributions of these two components are comparable. The analysis carried out by Yuqian and Wolfendale (1990) shows that discrete sources (both resolved and unresolved) are responsible for the fraction $f = 0.31 \pm 0.06$ of the total gamma radiation of the galaxy at $E_\gamma \geqslant 100$ MeV. This corresponds to the gamma-ray flux from the galactic plane due to these sources,

$$J_\gamma(\geqslant 100\,\mathrm{MeV}) \simeq 6 \cdot 10^{-5}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}. \tag{1}$$

Though at energies $E_\gamma \sim 100$ MeV several processes (connected with both accelerated protons and electrons) with different gamma-ray spectra may have comparable contributions, here we assume the single power-law spectrum of gamma rays extends at least up to $E \sim 1$ TeV. The differential spectra of COS B sources at $100\,\text{MeV} \leqslant E \leqslant 1$ GeV are rather hard with the typical power-law index $\alpha \sim 2$ (Bignami and Hermsen 1983). The continuation of the gamma-ray spectra of discrete sources up to $E_\gamma \sim 1$ PeV explains a number of puzzling features of CR (Wdowczyk and Wolfendale, 1983). In particular, the power-law index $\alpha \sim 2$ agrees with the 'diffuse' gamma-ray data observed by the CrAO group from the galactic plane at $E_\gamma \sim 1$ TeV (Fomin *et al* 1987, Vladimirsky 1988), as well as with the Baksan data on CR anisotropy (Alexeenko and Navarra 1985). The hard gamma-ray spectra of the sources are consistent with the existing evidence that the CR spectra in the sources are essentially harder than in the interstellar medium. The measurements of the energy spectrum and composition of primary CR on the Space Shuttle indicate that the CR propagation pathlength decreases ($\lambda \propto E^{-0.6}$) up to $E \sim 1\,\text{TeV}\,\text{amu}^{-1}$, which is consistent with a source spectrum of the form $E^{-2.1\pm0.1}$ (Grunfeld *et al* 1990).

Assuming the power-law spectrum of gamma rays from both resolved and unresolved sources in galactic disc, $J_\gamma(E_\gamma) \propto E_\gamma^{-2.1}$, and using (1), we obtain:

$$J_\gamma(E_\gamma) = 5.2 \times 10^{-6}(E_\gamma/\text{GeV})^{-2.1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\,\text{GeV}^{-1}. \tag{2}$$

Now suppose that some fraction of gamma rays interacts with the ambient low-frequency radiation before escaping the sources, producing e^+e^- pairs. Both the expected flux and the spectrum of the secondary electrons (e^+ and e^-) depend on the production rate in the sources and their diffusion in the interstellar medium. In order to calculate the expected flux, some assumptions on the emission power $\dot{\mathcal{N}}_\gamma(E_\gamma)$ and the spatial number density, $\rho_s(\boldsymbol{R}) \equiv (\mathrm{d}N_s/\mathrm{d}V)_{\boldsymbol{R}}$, of those sources should be made. Below we consider the simplest case of spatially homogeneous distribution of the sources, $\rho_s(\boldsymbol{R}) = \rho_s = \text{constant}$, with similar source parameters. This assumption is not critical, since the electron diffusion in the interstellar medium significantly smooths the inhomogeneities of the real source density $\rho_s(\boldsymbol{R})$. At the same time, it essentially simplifies the problem, allowing us to use the specific (per unit volume) gamma-ray emissivity $Q_\gamma(E_\gamma)$ averaged over the volume filled with discrete sources:

$$Q_\gamma(E_\gamma) = \rho_s \dot{\mathcal{N}}_\gamma(E_\gamma)\,\text{cm}^{-3}\,\text{s}^{-1}\,\text{GeV}^{-1} \tag{3}$$

where $\dot{\mathcal{N}}_\gamma(E_\gamma)$ is the characteristic gamma-ray emissivity of an individual source. Now assuming that the sources fill the disc with some radius R_0 around us, the observed differential flux $J_\gamma(E_\gamma)$ in the plane of the disc is related to $Q_\gamma(E_\gamma)$ as:

$$J_\gamma(E_\gamma) = \int_0^{R_0} \frac{Q_\gamma(E_\gamma)}{4\pi R^2} R^2\,\mathrm{d}R. \tag{4}$$

Using (2), we obtain:

$$Q_\gamma(E_\gamma) = \frac{4\pi}{R_0} J_\gamma(E_\gamma) = Q_0(E_\gamma/\text{GeV})^{-2.1} \tag{5}$$

with

$$Q_0 = 4.35 \times 10^{-36} \frac{5\,\text{kpc}}{R_0} \left(\frac{1}{\text{cm}^3\,\text{s}\,\text{eV}}\right). \tag{6}$$

Here R_0 is normalized to 5 kpc, since the characteristic distances to COS B sources are estimated to be within 2–7 kpc, which follows from their narrow distribution over heights in the galactic plane (Bignami and Hermsen 1983).

3. Positron production in sources

Now suppose that, prior to leaving the source, gamma rays interact with the ambient low-frequency photons with mean energy ε_0, and consider the case of an optically thin target. The pair production spectrum $q_\pm(E)$ in general case has been studied by Aharonian *et al* (1983). In the particular case of a power-law distribution of gamma rays, the spectrum $q_\pm(E)$ has the following characteristic shape: starting from the minimal energy $E_* = m^2c^4/4\varepsilon_0$ of the electrons (both e^+ and e^-) produced, the spectrum sharply rises reaching the maximum at $E \simeq (2\div4)E_*$, and then at $E \gg E_*$ it decreases as $q_\pm(E) \propto E^{-(\alpha+1)} \ln(E/E_*)$. For further calculations the following analytical approximation for the pair production spectra per interaction will be used:

$$q_\pm(E)\,\mathrm{d}E = f(\alpha)\frac{\mathrm{e}^{-1/(x-1)}}{E_* x(1+0.07x^\alpha/\ln x)}\,\mathrm{d}E \tag{7}$$

where $x = E/E_* \geqslant 1$, and $f(\alpha) = 1.11(1-1.44\alpha+1.06\alpha^2)$. For $\alpha \simeq 1\div3$ this approximation provides an accuracy better than 20% (note that at $\alpha \simeq 2$ the accuracy is about 5%).

The spectrum (7) corresponds to the creation of two electrons per interaction, i.e. $\int q_\pm(E)\,\mathrm{d}E = 2$. To obtain the total electron production rate in the source, $\dot{N}_e(E) = q_\pm(E) r_{\gamma\gamma}$, we should determine the total rate $r_{\gamma\gamma}$ of $\gamma\gamma$ collisions there:

$$r_{\gamma\gamma} = \tau_{\gamma\gamma}\dot{N}_\gamma(>E_{\mathrm{th}}). \tag{8}$$

Here $\dot{N}_\gamma(>E_{th})$ is the total rate of gamma-ray production at energies $E_\gamma \geqslant E_{\mathrm{th}}$ ($E_{\mathrm{th}} = (m_e c^2)^2/\varepsilon_0$ being the threshold energy for gamma rays interacting with the ambient photons with characteristic energy ε_0 and number density n_0); $\tau_{\gamma\gamma} = n_0\sigma_{\gamma\gamma}l$ is the optical depth accumulated by a gamma-quantum with energy $E_\gamma > E_{\mathrm{th}}$ at pathlength l before escaping the source. For the power-law spectra of gamma rays $\dot{N}_\gamma(E_\gamma) \propto E_\gamma^{-\alpha}$ the averaged pair-production cross section per gamma quantum above the threshold

$$\bar{\sigma}_{\gamma\gamma}(\alpha) = \int \sigma_{\gamma\gamma}(E_\gamma)\dot{N}_\gamma(E_\gamma)\,\mathrm{d}E_\gamma/\dot{N}_\gamma(>E_{\mathrm{th}}) \tag{9}$$

is a weak function of α. The numerical calculations show that $\bar{\sigma}_{\gamma\gamma} = 0.85\times10^{-25}\,\mathrm{cm}^2$ at $\alpha = 1.5$, $\bar{\sigma}_{\gamma\gamma} = 0.91\times10^{-25}\,\mathrm{cm}^2$ at $\alpha = 2$ and $\bar{\sigma}_{\gamma\gamma} = 0.83\times10^{-25}\,\mathrm{cm}^2$ at $\alpha = 2.5$

In (8) we assume that the source is optically thin for gamma rays, i.e. $\tau_{\gamma\gamma} < 1$. This assumption allows us to equate the production rate of gamma rays in the source directly with the emissivity of the source (since the absorption of gamma rays in this case can be neglected, $\dot{N}_\gamma(E_\gamma) \simeq \dot{\mathcal{N}}_\gamma(E_\gamma)$, and thereby to connect $\dot{N}_\gamma(E)$ with the observed flux of gamma rays via (3)–(6). Moreover, in this case the possible distortion of the positron production spectrum due to Compton scattering in the source can also be neglected (since $\tau_{\mathrm{Comp}} \sim \tau_{\gamma\gamma} < 1$), provided, of course, that the electron trapping in the source is negligible.

Now using (3) and (8), the specific rate of injection of secondary electrons into the interstellar medium (per unit volume), $Q_\pm(E) = \rho_s\dot{N}_\pm(E)$, can be written as:

$$Q_\pm(E) = \tau_{\gamma\gamma}Q_\gamma(>E_{\mathrm{th}})q_\pm(E). \tag{10}$$

It should be noted that the positron injection rate, $Q_+(E) = Q_\pm(E)/2$, depends on the gamma-ray emissivity $Q_\gamma(E_\gamma)$, which is defined by the observed flux of gamma rays, $J_\gamma(E_\gamma)$, and the characteristic size R_0 of the region filled with the sources, as well as on the free parameter $\tau_{\gamma\gamma}(<1)$.

4. The equilibrium spectrum of positrons in the interstellar medium

The secondary electron (e^+ and e^-) specific injection rate $Q_\pm(E)$ being known, one may determine the equilibrium electron spectrum $n_\pm(E)$ in the interstellar medium using the familiar stationary diffusion equation

$$\frac{d}{dE}(P(E)n_\pm(E)) - \frac{n_\pm(E)}{t(E)} + Q_\pm(E) = 0. \tag{11}$$

Here $P(E)$ is the electron energy loss rate, $t(E)$ is the CR electron confinement time in the interstellar medium. Following Protheroe (1982), we will use the dependence $t(E) \propto E^{-\delta}$ with the index δ in the interval $0 \leqslant \delta \leqslant 0.55 (E \geqslant 10\,\text{GeV})$:

$$t(E) = t_0(E/10\,\text{GeV})^{-\delta} \qquad t_0 \simeq 10^7\,\text{y}. \tag{12}$$

In the electron energy range of interest the energy loss rate $P(E)$ is predominantly due to synchrotron radiation and inverse Compton scattering:

$$P(E) = \tfrac{4}{3}\sigma_T c(W_B + W_{opt} + W_{MBR})\left(\frac{E}{m_e c^2}\right)^2 \tag{13}$$

where W_B, W_{MBR} and W_{opt} are the energy densities of the magnetic field, microwave background radiation and optical radiation in the interstellar medium, respectively. It should be noted, however, that this expression for $P(E)$ is only correct for electron energies $E \ll 100\,\text{GeV}$, since at energies $E \geqslant 100\,\text{GeV}$ the condition of Thomson scattering of electrons on optical photons does not hold and the energy losses in the optical photon field decrease. Since in the interstellar medium $W_{opt} \leqslant W_B + W_{MBR}$, the neglect of this effect may lead to a noticeable error (up to a factor of two). For present calculations we have taken $W_B = 0.4\,\text{eV cm}^{-3}$; $W_{MBR} = 0.25\,\text{eV cm}^{-3}$ and $W_{opt} = 0.45\,\text{eV cm}^{-3}$.

Using (10), the general solution to (11) can be written as:

$$n_\pm(E) = \tau_{\gamma\gamma} F(E) \tag{14}$$

where

$$F(E) = \frac{Q_\gamma(>E_{th})}{P(E)} \int_E^\infty q_\pm(x) \exp\left(-\int_E^x \frac{dy}{t(y)P(y)}\right) dx. \tag{15}$$

The expected differential flux of electrons connected with e^+e^- pair production in frames of the model is

$$J_\pm(E) = \frac{c}{4\pi} n_\pm(E). \tag{16}$$

Taking into account that half of the flux $J_\pm(E)$ is in positrons, $J_+(E) = \frac{1}{2}J_\pm(E)$, and using (14) and (16), the relevant positron content $r_+ \equiv r_+(E) = J_+(E)/J_{obs}(E)$ in the CR electrons flux observed, J_{obs}, can be written as:

$$r_+(E) = \frac{c\tau_{\gamma\gamma} F(E)}{8\pi J_{obs}(E)}, \tag{17}$$

where $F(E)$ is given by (15).

The equilibrium differential spectra of electrons, $G_\pm(E) \equiv J_\pm(E) \times E^3$, resulting from e^+e^- pair production are shown in figure 1(a) and (b). The absolute fluxes of

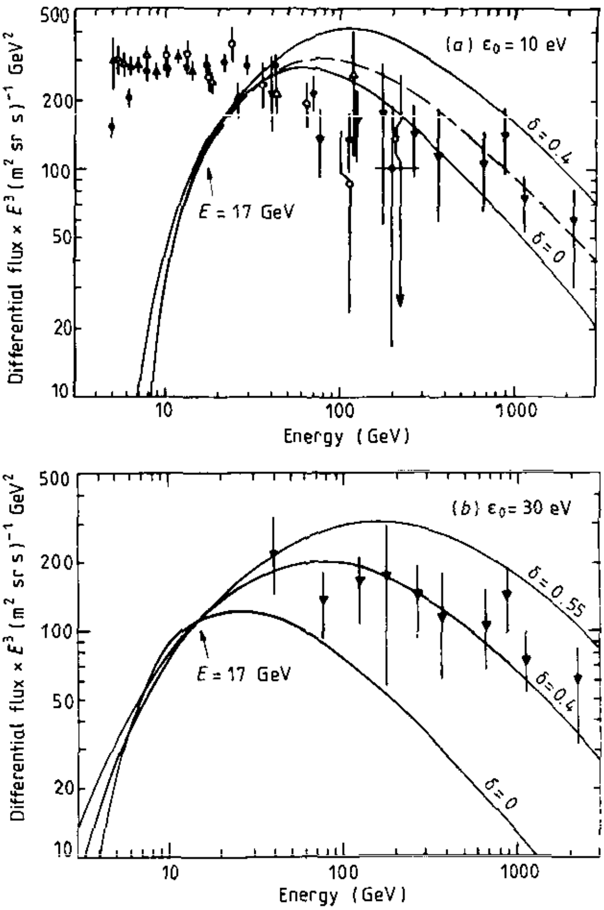

Figure 1. (a) Equilibrium differential spectra of electrons (e^+ and e^-) resulting from e^+e^- pair production in the sources. The spectra are normalized so as to satisfy the observed ratio $r_+(17\,\mathrm{GeV}) = 0.2$. The calculations are carried out for $\varepsilon_0 = 10\,\mathrm{eV}$ and parameters $\delta = 0$ and $\delta = 0.4$ (full curves). The broken curve corresponds to the electron spectrum for $\delta = 0.4$ when ignoring the relativistic corrections to the Compton scattering cross section. The experimental data for the electron fluxes detected by different groups are taken from the compilation by Ormes *et al* (1986). (b) The same as (a), but for $\varepsilon_0 = 30\,\mathrm{eV}$ and parameters $\delta = 0$, $\delta = 0.4$, and $\delta = 0.55$. For simplicity, only the high energy experimental data reported by Nishimura *et al* (1981) are presented.

this component are calculated assuming that almost all the CR positrons at $E > 10\,\mathrm{GeV}$ are due to this mechanism. Indeed, according to conventional models, at $E > 10\,\mathrm{GeV}$ the content of secondary positrons in CR, resulting from interactions of CR protons and nuclei with interstellar gas, is only $(2\div 5)\%$ (see figure 2). Then the absolute values of $J_\pm(E) = G_\pm(E)/E^3$ are found from the normalization at $E = 17\,\mathrm{GeV}$: $G_\pm(17\,\mathrm{GeV}) = 2G_+(17\,\mathrm{GeV}) = 2G_{\mathrm{obs}}(17\,\mathrm{GeV}) \times r_+(17\,\mathrm{GeV})$, where we use $G_{\mathrm{obs}}(17\,\mathrm{GeV}) = 300\,\mathrm{GeV}^2\,\mathrm{m}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$ and $r_+(17\,\mathrm{GeV}) = 0.2$ (see figure 1(a) and figure 2, respectively. The spectrum $J_\pm(E)$, calculated without account of 'damping' of radiative energy losses of electrons in an optical photon field (due to the Klein–Nishina cross section), is shown in figure 1(a) by a broken curve. All the

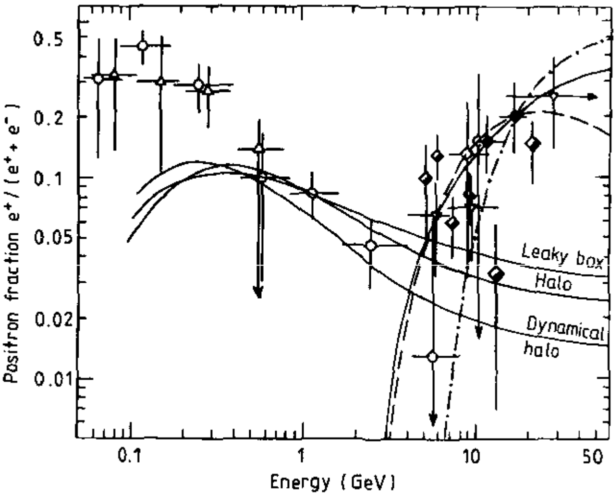

Figure 2. The ratio of $r_+(E) \equiv e^+/(e^+ + e^-)$ expected in the model. The calculations are carried out using equation (17), and correspond to the normalization $r_+(17\,\text{GeV}) = 0.2$ and for the parameters: $\delta = 0.4$, $\varepsilon_0 = 30\,\text{eV}$ (full curve); $\delta = 0$, $\varepsilon_0 = 30\,\text{eV}$ (broken curve); $\delta = 0.4$, $\varepsilon_0 = 10\,\text{eV}$ (chain curve). The experimental data are taken from compilations by Ormes *et al* (1986) and Müller and Tang (1990). The content of secondary positrons resulting from CR interactions with interstellar gas, predicted in frames of different CR propagation models, are also presented (see, e.g., Ormes *et al* 1986).

other curves are obtained with this effect being taken into account. As follows from these curves, the values of $\delta \geqslant 0.55$ lead to inconsistency of the calculated spectra with the total electron flux detected at $E_\gamma \geqslant 100\,\text{GeV}$. This is the consequence of a more intense leakage of electrons from the confinement region at higher δ, which requires too high production rates of e^+e^- pairs at energies $E \simeq 1\,\text{TeV}$ to provide the observed positron flux at $E = 17\,\text{GeV}$. At the same time, in the case of $\delta \leqslant 0.4$ the observed spectral fluxes of electrons and positrons can be satisfied in the frames of the proposed model for both values of $\varepsilon_0 = 10\,\text{eV}$ and $\varepsilon_0 = 30\,\text{eV}$ of optical photon mean energies. Note that it is difficult to obtain a good agreement with experimental data if the photon energy ε_0 is both well above or well below the energy interval $10 \leqslant \varepsilon_0 \leqslant 30\,\text{eV}$.

The dependence of the positron content r_+ on the energy E is presented in figure 2. As in figure 1, all the curves are normalized to $r_+ = 0.2$ at $E = 17\,\text{GeV}$. In this figure, all the curves corresponding to different values of the parameters δ and ε_0 are in agreement with the experimental data, providing, in particular, a sharp increase of positron content above several GeV. At lower energies the contribution of the proposed mechanism becomes negligible. However, at these energies the experimental data can be explained by standard models, i.e. by positron production at interactions of CR with the interstellar matter.

The relatively large uncertainties of experimental data do not allow us to make a better choice between different values of δ and ε_0. We can see that, while at $\delta = 0.4$ the positron content continues to rise with energy up to $E \simeq 100\,\text{GeV}$, the curve corresponding to $\delta = 0$ reaches the maximum $r_+ = 0.2$ at $E \sim 20\,\text{GeV}$, and then decreases with increasing energy. Such behaviour of $r_+(E)$ is connected with a steeper decrease of $J_\pm(E)$ as compared with the electron flux $J_{\text{obs}}(E)$ (see figure 1(*b*), the

Table 1. Characteristic optical thicknesses with respect to photon–photon collisions at different ε_0

	$\tau_{\gamma\gamma}$		
ε_0(eV)	$\delta = 0$	$\delta = 0.4$	$\delta = 0.55$
10	0.35	0.65	—
30	0.20	0.72	1.8

case with $\delta = 0$). In this case the proposed mechanism can provide no more than 10% of the flux at energies $E \geqslant 100$ GeV. So, some additional component of directly accelerated electrons will be needed. At the same time, the necessity for this additional component would be absent if $\delta = 0.4$ (see figure 1).

The gamma-ray emissivity $Q_\gamma(E_\gamma)$ and the optical photon energy ε_0 being given, the only free parameter defining the absolute value of $r_+(E)$ in (17) is the characteristic optical depth $\tau_{\gamma\gamma}$ of the source. Then, using (5) and (6) for $Q_\gamma(E)$, the observed electron flux $J_{\text{obs}}(E)$ and the positron fraction $r_+(E) = 0.2$ at $E = 17$ GeV, we find $\tau_{\gamma\gamma}$ presented in table 1. The obtained values of $\tau_{\gamma\gamma}$ are within the interval $(0.1, 1)$, which is consistent with the previous assumption on optically thin sources.

5. Discussion

The anomalously high content of positrons in CR at energies $E \geqslant 10$ GeV (Buffington *et al* 1975, Müller and Tang 1985, Golden *et al* 1987) is in an apparent contradiction with the standard models suggesting the positron production due to interactions of CR with the interstellar matter. Most probably, to explain this part of the spectrum, some extra component of high energy positrons is needed (Müller and Tang 1990).

In this paper we propose a model according to which this extra component of positrons is produced in discrete sources due to interactions of high-energy gamma rays with the optical (and/or UV) radiation. This model allows one to satisfactorily explain the observed sharp increase of the ratio $r_+(E) = e^+/(e^+ + e^-)$ at $E \geqslant 10$ GeV (see figure 2) without any contradiction with the total differential spectrum of electrons and positrons detected (figure 1). At the same time, in the case of the optical–UV target photons, the pair production spectra in compact sources drastically decrease below $E \sim 10$ GeV, so that at $E < 3$ GeV the proposed component of CR positrons is well below the positron content observed. In this range, however, the CR positron data are readily interpreted in frames of conventional CR propagation models (see, e.g., Müller and Tang 1990).

The results presented in figures 1 and 2 are normalized to $r_+ = 0.2$ observed at $E = 17$ GeV. For the model to be realistic, it has to provide the absolute fluxes, which depend first of all on the number and luminosity of the gamma-ray sources. Unfortunately, the energy range $10\text{ GeV} \leqslant E_\gamma \leqslant 1$ TeV, which is most critical for our model, is quite unexplored. Therefore, we have to make certain assumptions about the relevant gamma-ray sources.

In this paper we consider the possibility that the high energy positrons are produced in gamma-ray sources (both resolved and unresolved) responsible for about 30% of the galactic disc gamma radiation at $E_\gamma \geqslant 100$ MeV. We suppose that some fraction of the gamma rays emitted interact with the ambient optical/UV radiation in these sources, producing e^+e^- pairs which then are injected into the interstellar medium. For the gamma-ray emissivity $Q_\gamma(E_\gamma)$ given by (5) and (6), the absolute fluxes of positrons at $E \geqslant 10$ GeV are provided at characteristic probability of gamma-ray interaction before escaping from the source $0.1 < \tau_{\gamma\gamma} < 1$ (see table 1).

Since the nature of these gamma-ray sources still remains quite uncertain (e.g. in literature as possible candidates for these sources are discussed such objects as young radio pulsars, supernova remnants, young star formation regions, x-ray binaries, etc), each of these cases needs a separate discussion, which is out of the scope of this paper. Here we only note that the requirement of $\tau_{\gamma\gamma} \geqslant 0.1$ does not seem to be extraordinary, if we take into account the large cross section of pair production as well as the possible existence of high density radiation fields in the ambient matter heated, in particular, by accelerated particles. This requirement may be satisfied even in non-compact objects, for example, near OB stars, which are widely discussed as possible gamma-ray sources. To demonstrate the latter, let us consider the interaction of gamma rays with the Lyman continuum photons ($\varepsilon_0 \geqslant 13.6$ eV) of O stars. The luminosity $\mathscr{L}(L_c)$ of, say, an O4 star is about $\mathscr{L}(L_c) \simeq 1.3 \times 10^{50}$ photons/s (see, e.g., Kaplan and Pikelner 1979), therefore, the optical depth $\tau_{\gamma\gamma} = l\langle\sigma_{\gamma\gamma}\rangle n_{L_c} = \langle\sigma_{\gamma\gamma}\rangle \mathscr{L}(L_c)/4\pi l c \sim 0.3$ can be provided at distances $l \leqslant 10^{14}$ cm from the star.

Gamma rays responsible for e^+e^- production obviously are of secondary origin, resulting from interactions of directly accelerated particles, electrons and/or protons. For the latter case some comments should be made. At pp interactions, apart from the π^0 mesons (decaying to gamma rays) a comparable amount of $\pi^\pm$ mesons are produced as well. Then, to avoid a contradiction with experimental data on the positron fraction in CR electron flux which may arise at low energies, $E \sim 1$ GeV, the electrons and positrons resulting from the decays of $\pi^\pm$, should be captured in the production region, e.g. by magnetic fields. Gamma rays escaping from this region may then interact with the ambient photons at a distance, where the strength of magnetic field is essentially lower, so that the photoproduced pairs can leave that region without significant energy losses.

Finally, we would like to emphasize once more that, due to the lack of experimental data concerning the gamma-ray fluxes at energies $10\,\mathrm{GeV} \leqslant E_\gamma \leqslant 1\,\mathrm{TeV}$, we have used an extrapolation of the fluxes detected at $E_\gamma \geqslant 100$ MeV. It does not, however, exclude that the real fluxes at energies $E_\gamma \sim 1$ TeV may be much higher (by more than a factor of ~10) than follows from this simple extrapolation (Fomin *et al* 1977, Dowthwaite *et al* 1985). Unfortunately, the energy range $E_\gamma \sim 10$–100 GeV, which is most important in our model, is as yet available from neither satellite nor ground-based experiments. Nevertheless, the measurements of the gamma-ray flux at $E_\gamma \sim 10$ GeV by GRO (Kanbach *et al* 1988) and $E_\gamma \geqslant 100$ GeV by GRANITE (Akerlof *et al* 1989) may significantly clarify the question.

The detailed measurements of the differential spectra of high-energy electrons and positrons, in particular, at $E \geqslant 100$ GeV, planned in the future 'ASTROMAG' experiment (Ormes *et al* 1986), will be very important for verification of the proposed model.

Acknowledgments

The authors are grateful to A Buffington, D Müller and K Tang for useful discussions.

References

Aharonian F A, Atoyan A M and Nahapetian A 1983 *Astrofiz.* **19** 323

Akerlof C W, Cawley M F, Fegan D J, Hillas A M, Lamb R C, Lewis D A, Meyer D I and Weekes T C 1989 *Harward–Smithsonian Preprint* No 2945

Alexeenko V V and Navarra G 1985 *Lett. Nuovo Cimento* **42** 321

Bignami G F and Hermsen W 1983 *Ann. Rev. Astron. Astrophys.* **21** 67

Buffington A, Orth C D and Smooth G F 1975 *Astrophys J.* **199** 669

Dowthwaite J C, Harrison A B, Kirkman I W 1985 *Astron. Astrophys.* **142** 55

Fomin V P, Vladimirisky B M and Stepanian A A 1977 *17th Int. Cosmic Ray Conf.* (*Paris*) vol 1 p 12

Golden R L, Mauger B G, Horan S, Badhwar G D, Lacy J L, Zipse J E, Daniel R R and Stephens S A 1987 *Astron. Astrophys.* **188** 145

Grunfeld J M, L'Heureux J, Meyer P, Müller D and Swordy S 1990 *21st Int. Cosmic Ray Conf.* (*Adelaide*) vol 2 p 69

Harding A K and Ramaty R 1987 *20th Int. Cosmic Ray Conf.* (*Moscow*) vol 2 p 92

Kanbach G *et al* 1988 *Space Sci. Rev.* **49** 69

Kaplan S A and Pikelner S B 1979 *The Physics of Interstellar Medium* (Moscow: Nauka) (in Russian)

Müller D and Tang K 1985 *19th Int. Cosmic Ray Conf.* (*La Jolla*) vol 2 p 378

—— 1990 *21st Int. Cosmic Ray Conf.* (*Adelaide*) vol 2 p 249

Nishimura J, Fujii M, Taira T, Auzu E, Nomura Y, Kobayashi T, Niu K, Nishio A, Golden R L, Koss T A, Lord J J and Wilkes R J 1981 *17th Int. Cosmic Ray Conf.* (*La Jolla*) vol 2 p 94

Ormes J F, Israel M, Wiedenbeck M and Mewaldt T 1986 *NASA Interim Report* Code 661, Greenbelt, MD, 10771, USA

Protheroe R J 1982 *Astrophys. J.* **254** 391

Vladimirsky B M 1988 *Izv. CrAO* **80** 83 (in Russian)

Wdowczyk J and Wolfendale A W 1983 *Nature* **305** 609

Yuqian M and Wolfendale A W 1990 *21st Int. Cosmic Ray Conf.* (*Adelaide*) vol 1 p 117