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Letter to the Editor

High energy electrons and positrons in cosmic rays as an indicator of the existence of a nearby cosmic tevatron

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Abstract. The sharp increase of the positron content in the cosmic ray electron flux at $E \geq 10\,\mathrm{GeV}$ is regarded as an enigma (Müller & Tang 1990). Here we show that in fact the 'enigma' disappears if the propagation of the cosmic ray electrons is treated correctly. The proper treatment of cosmic rays, namely, separation of the contribution of one (or few) nearby (r $\sim$ 100 pc) and relatively young ($t \sim 10^5$ yr) source(s) from the contribution from distant ($r \geq 1\,\mathrm{kpc}$) sources explains the features of both energy spectrum and charge composition of electrons observed between $\sim$ 100 MeV and 2 TeV. We argue that the nearby γ-ray pulsar Geminga is a probable source responsible for the observed very high energy electrons.

Key words: cosmic rays - diffusion - pulsars: individual: Geminga

1. Introduction

The electron component of cosmic rays (CRs) is described by the energy spectrum and the positron-to-electron ratio, $R_+ = e^+/(e^- + e^+)$. While at energies of about 1 GeV the observed content of positrons is explained by interactions of CRs with the interstellar gas, at energies $\geq 10\,\mathrm{GeV}$ it is almost an order of magnitude larger than the flux of secondary positrons. Therefore some other source of positrons is needed. The sharp increase of R_+ above 10 GeV can be associated with a hard spectrum of positrons produced, e.g. by pulsars (Harding & Ramaty, 1987), due to CR acceleration in molecular clouds (Dogiel & Sharov, 1990), at annihilation of dark matter (Tylka, 1989), due to interactions of γ-rays with optical radiation near young stars (Aharonian & Atoyan, 1991), etc. All these models however invoke special circumstances. In addition, the propagation of electrons in these models was treated in the framework of standard leaky-box or diffusion model, whose applicability is doubtful for high energy electrons.

Indeed, the standard interpretation of the energy spectrum of cosmic ray (CR) electrons assumes a uniform and continuous distribution of sources in the Galaxy, both in space and time. Whereas for the nucleonic component of CRs this hypothesis may be considered as a reasonable approximation, the validity of such an assumption is strongly limited for electrons, at least in the high energy part of the measured spectrum which extends up to $E \approx 2\,\mathrm{TeV}$ (Taira et al. 1993). The life-time of electrons in the interstellar medium (ISM) against synchrotron and inverse Compton energy losses is about $t_r = E/(-dE/dt)_r \approx 3 \cdot 10^8\,(E/1\,\mathrm{GeV})^{-1}$ yr. Thus the age of the observed TeV electrons cannot exceed $\approx 1.5 \cdot 10^5$ yr. This implies the existence of a nearby source of TeV electrons (Shen 1970, Nishimura et al. 1980). The distance to the source cannot exceed the characteristic CR diffusion radius $r \sim \sqrt{D \cdot t}$ where $D \equiv D(E)$ is the energy dependent diffusion coefficient. It may be approximated in the form $D(E) = D_0(1 + E/E_*)^\delta$ which contains both the power-law behavior of D for $E \gg E_*$, and its tendency to energy-independence below E_*. It is believed that typically $E_* \sim 1 - 10\,\mathrm{GeV}$, and $\delta \sim 0.5 - 0.6$. Also, D_0 is chosen from the condition that the typical value of the diffusion coefficient at $E = 10\,\mathrm{GeV}$ is $D_{10} \equiv D(10\,\mathrm{GeV}) \sim 10^{28}\,\mathrm{cm}^2/\mathrm{s}$

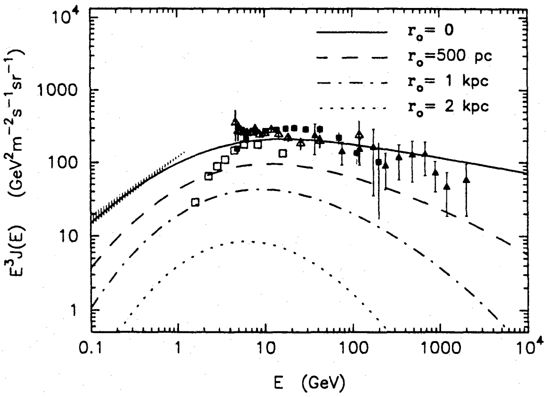

Fig. 1. The fluxes of electrons from sources homogeneously distributed in the galactic disk (half-thickness $h = 100\,\mathrm{pc}$), calculated for standard parameters $\alpha = 2.4$, $\delta = 0.6$, $E_* = 3\,\mathrm{GeV}$, and $D_{10} = 10^{28}\,\mathrm{cm}^2/\mathrm{s}$. The following parameters of the ISM have been used: mean gas density $n = 0.5\,\mathrm{cm}^{-3}$, magnetic field $B = 3\,\mu\mathrm{G}$, starlight density $w_{\mathrm{IR/O}} = 0.5\,\mathrm{eV/cm}^3$, density of the 2.7 K background radiation $W_{\mathrm{MBR}} = 0.25\,\mathrm{eV/cm}^3$. The total spectrum (solid line) is decomposed to show the contributions from the sources at distances $r \geq r_0$. The compilation of experimental fluxes is taken from Taira et al (1993). The dashed region corresponds to the flux of CR electrons deduced from radio data by Webber et al (1980).

Send offprint requests to: F. A. Aharonian (see e.g. Berezinsky et al. 1990). Then, for the 2 TeV electrons the maximum distance to the source(s) is reduced to ~ 300 pc!

In Fig.1 the energy spectrum of CR electrons calculated assuming a homogeneous and continuous distribution of the sources in the galactic disk (solid curve), is decomposed to show the contributions from sources located at distances $r > r_0$ for different r_0. The details of the calculations are presented elsewhere (Atoyan et al. 1994). It follows from Fig.1 that only about 10% of the the flux of 2 TeV electrons is contributed by sources located beyond 500 pc. This means that the assumption of a continuous distribution of CR sources would have to be valid down to scales of a few hundred parsecs. Otherwise the correct approach to the interpretation of the observed CR electrons fluxes requires a separate treatment for the two different components of the *primary* electrons: (1) the contribution from one or a few nearby local sources (L-component), and (2) the contribution from sources at large distances, typically beyond 1 kpc, which may still be treated in the framework of the traditional assumption of a uniform and continuous (in space and time) source distribution in the Galaxy (G-component). Apart from these components of directly accelerated electrons there is some contribution to the total flux from secondary electrons (S-component) produced in interactions of galactic CRs with interstellar gas. Note that only for this component of electrons produced at *any* point of the ISM, the hypothesis of a continuous (both in space and time) distribution of sources is justified.

2. Two-component approach to primary electrons

The above approach has been first suggested by Lingenfelter (1969). Later Shen (1970) discussed the special importance of such a separation for high energy CR electrons. However he limited his study to energy independent diffusion. Recently we have developed a single source (localized) formalism, extending it to the case of energy-dependent propagation. A simple Green's function solution to the general nonstationary diffusion equation has been obtained for an arbitrary injection spectrum and an arbitrary energy losses (Atoyan et al. 1994). In the particular case when only radiative energy losses $(dE/dt)_r = -bE^2$ are taken into account, and the primary spectrum of electrons is a power-law, $Q(E) = Q_0 E^{-\alpha}$, the density of electrons at time t after their injection from a source at distance r is equal to

$$f_e(r,t,E) = \frac{Q(E)}{\pi^{3/2} r^3}\,(1 - btE)^{\alpha-2} \left(\frac{r}{r_{dif}}\right)^3 e^{-(r/r_{dif})^2}, \qquad (1)$$

where $E < E_{max} = (bt)^{-1}$ (otherwise $f_e = 0$), and

$$r_{dif}(E,t) \simeq 2\sqrt{D(E)\,t\,\frac{1-(1-E/E_{max})^{1-\delta}}{(1-\delta)\,E/E_{max}}}\,. \qquad (2)$$

Note that at energies below several GeV the bremsstrahlung and ionization energy losses dominate in the ISM. Thus for timescales comparable with typical times of the bremsstrahlung ($t_{br} \approx 3 \cdot 10^7 (n/1\mathrm{cm}^{-3})^{-1}$ yr) and ionization ($t_i \approx 10^8 (n/1\mathrm{cm}^{-3})^{-1} (E/1\mathrm{GeV})^{-1}$ yr) energy losses, i.e. for $t \geq 10^7$ yr, Eq.(1) is not valid. However, for timescales $t < 10^7$ yr this simple solution is quite accurate at lower energies (at least down to $E \approx 100$ MeV) as well. In the case of energy-independent diffusion ($\delta = 0$) it reduces to the expression obtained earlier by Berkey and Shen (1969). Energy-independent diffusion from a single burst-like source leads to a time variation of the flux, $J_e = (c/4\pi) f_e$, without change of the spectral form. Energy-dependent diffusion results in addition in a strong modification of the primary energy spectrum in time. For a given energy $E < E_{max}$, an observer at a distance r from the source would detect the maximum flux J_e^{max} at instant $t \sim t_{max}(E) = r^2/6D(E)$. At $t \ll t_{max}(E)$ the electrons have not yet reached the observer, while at $t \gg t_{max}(E)$ their density decreases due to spherical expansion as $r_{dif}^{-3} \propto t^{-3/2}$. Note that the magnitude of the maximum flux depends on distance as $J_e^{max} \propto r^{-3}$. The modification of the CR electron spectra depends mainly on the parameter $s = r/r_{dif}$. In particular, at sufficiently high energies for which the time of maximum flux has already passed ($s \ll 1$), the electrons are distributed in power-law form with exponent $\alpha' = \alpha + (3/2)\,\delta$. At lower energies, when the maximum flux at given energy is not yet reached, the primary spectrum is exponentially suppressed. Note that for $D(E) = const$ the electrons just repeat the shape of the injection spectrum with a time-dependent flux amplitude proportional to $G = s^2 e^{-s^2}$.

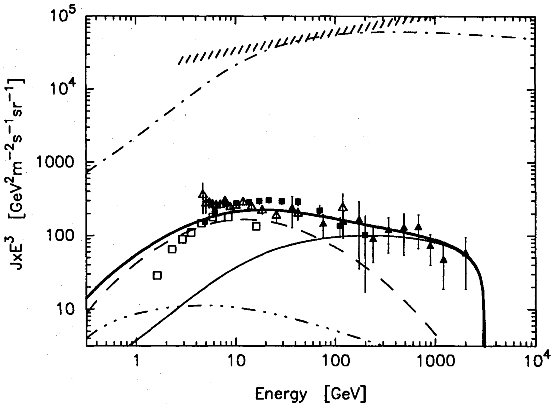

Fig. 2. The energy spectrum of CR electrons. The thin solid line corresponds to the L-component spectrum of electrons from a single burst-like source at $r = 100$ pc and $t = 10^5$ yr; the dashed curve corresponds to the spectrum of the G-component assuming a homogeneous distribution of sources in the galactic disk beyond 1 kpc, and the triple dot-dash line corresponds to the S-component. The heavy solid line is the sum of the L, G and S components. The calculated spectra are normalized to the observed fluxes of e^+ and $(e^+ + e^-)$ at $E = 10$ GeV. The compilation of experimental data is taken from Taira et al.(1993). The spectrum of protons from the source calculated for $W_p = 3 \cdot 10^{50}$ erg is also presented (dot-dash line). The measured fluxes of the CR protons are shown by the dashed region.

The two-component ("G+L") approach to primary electrons explains fairly well the electron fluxes observed from 1 GeV to 2 TeV (see Fig.2). Making the additional assumption that the G-component consists mainly of negatrons ($n_+ << n_-$), and that the L-component consists equally of negatrons and positrons ($n_+ = n_-$), allows us to explain also the measured charge composition of electrons (see Fig.3). In our model the reason for the dip in the positron content at several GeV (Fig.3) is connected with the long propagation time of the G-component electrons at lower energies, and their severe radiative energy losses at very high energies. The optimized curves shown in Figs.2,3 are calculated for parameters of the diffusion coefficient $D_{10} = 0.5 \cdot 10^{28}\ \mathrm{cm}^2/\mathrm{s}$, $E_* = 3$ GeV, $\delta = 0.6$, and a power-law index of the injection spectrum $\alpha = 2.2$. Actually, good fits to the measurements as presented in Fig.2,3 are possible also varying these parameters within some reasonable limits, provided $\alpha' = \alpha + (3/2)\delta$ lies within 3.1 to 3.3. In addition, the principal parameter $s = r/r_{dif}$, defining the modification of the primary spectrum from the nearby source, should not deviate from the best fit value $s \approx 1$ at $E = 10\,\mathrm{GeV}$ by more than a factor of 2.

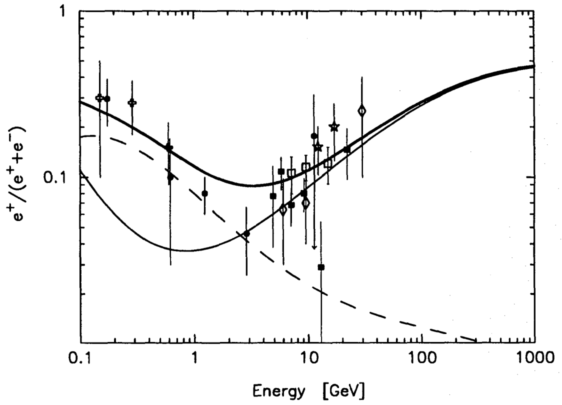

Fig. 3. The ratios $R_+ = e^+/(e^- + e^+)$. The denominator is given by the total flux from Fig.2. Numerators are from the L and S components; the corresponding ratios are shown by thin solid and dashed lines, respectively. The heavy solid line corresponds to the sum of L and S components. The compilation of experimental data is taken from Müller & Tang (1990) and Basini et al.(1991).

The flux of the S-component shown in Fig.2 is calculated in the framework of the diffusion model using the (e^+, e^-) production function from Protheroe (1982). The corresponding ratio of the secondary positrons to the total electron flux is shown in Fig.3. Although the contribution of the S-component does not exceed $\approx 20\%$ of the total electron flux at $E \sim 1\,\mathrm{GeV}$, the secondary positrons significantly contribute to the ratio R_+ below several GeV. It should be noted that although the flux of the S-component is in agreement with the calculations of Protheroe (1982), the ratio in Fig.3 (dashed line) at low energies differs from the relevant curve in Fig.4a of Protheroe (1982). The reason lies in the different total electron spectra calculated here and in the paper of Protheroe (1982).

3. Energy budget of the nearby source of electrons

In order to argue for the model suggested here we have to answer the basic question: what energy budget do we need for the explanation of the observed high energy electron fluxes from the nearby source, and what kind of object could be responsible? The total energy in (e^+, e^-) pairs is found from normalization of the theoretical curves to the measured fluxes of electrons, $J(E) = (c/4\pi)f_e$. In particular, for the parameters used in Fig.2, we need $W_\pm \approx 1.1 \cdot 10^{48}$ erg in (e^+, e^-) pairs above 100 MeV. Do we have such a source nearby?

In principle, the relativistic electrons can be produced by shock acceleration in a single SNR. This mechanism injects only negatrons, but one may expect from SNRs also secondary high energy positrons due to interactions of accelerated protons with the ambient thermal matter. The total amount of energy released in secondary electrons from $\pi^\pm$ decays is estimated as $W_\pm \approx (X/\Lambda_{pp}) f_\pm W_p$, where $X = nc\Delta t m_p$ is the 'grammage' accumulated by CRs during their residence time Δt within the supernova shell after acceleration; $\Lambda = m_p/\sigma_{pp}$, with $\sigma_{pp} \approx 30\,\mathrm{mb}$ representing the total inelastic cross-section, $f_\pm \approx 0.1$ is the partial inelasticity coefficient with respect to production of $e^\pm$. Then we arrive at the condition $(W_p/3 \cdot 10^{50}\,\mathrm{erg}) \cdot (\mathrm{n}/10\,\mathrm{cm}^{-3}) \cdot (\mathrm{t}/10^5\,\mathrm{yr}) \approx 1$. The energy in accelerated protons is estimated as $W_p = \theta \cdot E_{SN}$, where θ is the efficiency of CR proton acceleration and E_{SN} is the total kinetic energy of the supernova explosion with typical values ~ 0.1 and 10^{51} erg, respectively (e.g. Markievicz et al. 1990). In principle, it might be possible to admit more kinetic energy in the SN explosion ($E_{SN} \approx 10^{52}$ erg), and/or higher overall efficiency of the shock acceleration ($\theta \approx 0.5$). However, the allowed increase of W_p is limited by the observed CR proton flux. Indeed, in Fig.2 the dot-dash line corresponds to the CR proton flux, calculated for $W_p = 3 \cdot 10^{50}$ erg, The comparison of calculated and measured CR fluxes limits the total energy of cosmic rays to the value $W_p = 3 \cdot 10^{50}$ erg, and therefore requires $(n/10\,\mathrm{cm}^{-3}) \cdot (\Delta \mathrm{t}/10^5\,\mathrm{yr}) \geq 1$. Note that this requirement is obtained for the model parameters used in Fig.2. In fact the observed flux of particles depends on r, t and D. However, since the electron and proton fluxes have the same dependence on r, t and D, the ratio $W_\pm/W_p$ remains the same, and therefore the requirement above cannot be softened. This condition on the SNR dynamics is very difficult to fulfill (Dorfi 1991). Finally note also that the contribution of a nearby SNR with a justifiable energetics $W_p \simeq 10^{50}$ erg could supply only some fraction of the observed CR flux (see Fig.2). This has been recently noted also by Johnson (1994).

A more likely possibility is connected with the direct acceleration of (e^+, e^-) pairs by a pulsar. The synchrotron nature of the radiation of the Crab Nebula from radio to hard X-rays implies the existence of relativistic electrons of energies up to $> 10^{14}$ eV (Kennel and Coroniti, 1984). It is almost undisputed also that these electrons are (e^+, e^-) pairs produced by the pulsar (e.g. Arons, 1991). However, the Crab is too far to explain the observed high energy electron flux. Shen (1970) has proposed the Vela pulsar to be the source responsible. This object, being the strongest high-energy gamma-ray source in the sky, is young enough, $t \approx 1.1 \cdot 10^4$ yr, so that the electrons accelerated by the pulsar, even at its earliest stages, could reach us without significant energy losses up to $E \approx 10\,\mathrm{TeV}$. However, for a distance to Vela $r \approx 500\,\mathrm{pc}$, the required energy output in relativistic (e^+, e^-) pairs exceeds $2 \cdot 10^{50}$ erg which cannot be easily accepted. Moreover, to fit the data for $r = 500\,\mathrm{pc}$ and $t = 1.1 \cdot 10^4$ yr we would require an extraordinarily large diffusion coefficient, $D_{10} \approx 2 \cdot 10^{30}\,\mathrm{cm}^2/\mathrm{s}$. Thus, most probably we need a closer, but still not very old pulsar.

4. Discussion

Actually there are only a few candidates which satisfy both these criteria. Perhaps one of the most attractive candidates is the recently discovered γ-ray pulsar Geminga. The distance to Geminga is believed to be $\sim 100\,\mathrm{pc}$ (Bignami et al. 1993). The age of the pulsar is estimated as $t_0 = -\frac{\nu}{(n-1)\dot{\nu}}[1 - (\frac{\nu}{\nu_i})^{n-1}]$, where n is the so-called braking index, $n = \nu\ddot{\nu}/\dot{\nu}^2$, ν is the present pulsar frequency, $\dot{\nu}$ and $\ddot{\nu}$ are its first and second time derivatives, respectively, and ν_i is the pulsar frequency at $t = 0$ (see e.g. Manchester et al. 1985). In particular, for the canonical value $n = 3$ of the braking index, predicted for the magnetic dipole radiation model (Gunn & Ostriker 1969), and for values $\nu = 4.217\,\mathrm{Hz}$ and $\dot{\nu} = -1.952 \cdot 10^{-13}\,\mathrm{Hz/s}$, determined from the ROSAT (Halpern & Holt 1992) and EGRET (Bertsch et al.

1992) observations, we have $t_0 \approx 3 \cdot 10^5$ yr. Note that this age predicts a sharp cutoff in the electron spectrum at $E \approx 1$ TeV if the bulk of electrons are produced in a burst like event of duration $\Delta t \ll t_0$. In this case the model cannot explain the measured flux above 1 TeV (see Fig.4), if we would not suggest that the age of Geminga is at least a factor of 2 less than the above estimated value which in principle cannot be excluded if one takes into account the uncertainties in the braking index of Geminga (see e.g. Bisnovatyi-Kogan & Postnov, 1993).

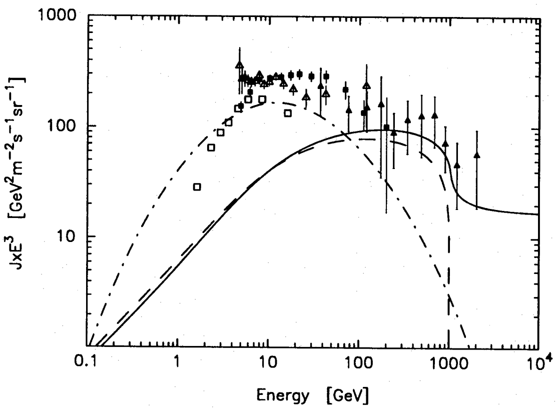

Fig. 4. The energy spectra of electrons from a single source at distance 50 pc, calculated for burst-like (dashed line) and continuous ($L_\pm \propto (1+t/\tau)^{-2}$, solid line) injection of (e^+, e^-) pairs into the interstellar medium. The spectrum of the G-component is also shown (dot-dash line). The normalization is the same as in Fig.2.

Another, and probably more realistic way to explain the electron fluxes above 1 TeV, even for the age of Geminga $t_0 \approx 3 \cdot 10^5$ yr, is connected with the suggestion of non-burst like injection, for example particle injection with luminosity $L_\pm$ proportional to the spin-down energy loss rate, $L_\pm = \kappa L_\Omega$. In the magnetic-dipole radiation models $L_\Omega = L_i[1 + t/\tau]^{-2}$, where $\tau = (\nu/\nu_i)^2 t_0$; ν_i and $L_i = (2\pi)^2 I \nu_i \dot{\nu}_i$ are the initial rotational frequency and the spin-down energy loss rate of the pulsar, respectively; I is the moment of inertia of the neutron star (e.g. Shapiro & Teukolsky 1983).

As it is seen from Fig.4, the spectrum corresponding to time-dependent injection $L_\pm \propto (1+t/\tau)^{-2}$ differs significantly from the spectra predicted by burst like injection. If in the case of burst-like injection the main parameter defining the modification of the primary spectrum is the parameter $s = r/r_{dif}$, in the case of magnetic dipole radiation the very high energy part of the spectrum depends also on the parameter τ. This model fits the measured spectral shape (see Fig.4) for the parameters: $r = 50$ pc, $\tau = 1.2 \cdot 10^4$ yr, and $D_{10} = 5.5 \cdot 10^{26}$ cm^2/s. In addition, to explain the absolute fluxes of electrons one needs the total energy $W_\pm = 2 \cdot 10^{47}$ erg released in (e^+, e^-) pairs. This diffusion coefficient is an order of magnitude less than the ones widely used for Galactic models. However, for any model which assumes a noticeable contribution to the observed CR flux from local nearby sources, smaller values of the diffusion coefficient are preferable, in particular, to avoid a possible contradiction with the observed small CR anisotropy (Ormes 1983).

For the apparent age of Geminga $t_0 = 3 \cdot 10^5$ yr, the characteristic "decay" time $\tau = 1.2 \cdot 10^4$ yr corresponds to $\nu_i/\nu \approx 5$, i.e. the period of the pulsar during the first $\approx 10^4$ yr was $P \approx 50$ ms. It is interesting to compare this period with present periods of younger γ-ray pulsars: Crab ($P = 33$ ms, $t_0 \approx 10^3$ yr) and Vela ($P = 89$ ms, $t_0 \approx 10^4$ yr).

The total energy output of Geminga for the suggested parameters is estimated as $E_{tot} = L_i \tau \approx 3.3 \cdot 10^{47}$ erg. Even for $r = 50$ pc one has to require a very high efficiency of transformation of the rotational energy of a pulsar to (e^+, e^-) pairs, i.e. $\kappa = 0.6$. Note nevertheless that the possibility of high efficiency, $\kappa \geq 0.5$, is supported by observations of the Crab pulsar (Kennel & Coroniti 1984). Thus, the choice of a small distance to Geminga is due to the limited available energy of the source. Note that $r \approx 50$ pc corresponds to the lower limit of the distance to Geminga. However, from the point of view of the efficiency of production mechanisms of ≥ 100 MeV γ-rays by the pulsar this distance appears preferable; for the discussion of this question see Harding et al (1993).

To summarize, we argue that, independently of the question whether or not Geminga is responsible for the observed high energy electrons and positrons, a location of the source of these particles well beyond 100 pc seems very unlikely because the energy requirement, which increases with the distance as $W_\pm \propto r^3$, becomes unacceptably high even for the most powerful Galactic CR accelerators like SNRs and pulsars.

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