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A local fading accelerator and the origin of TeV cosmic ray electrons

S. Recchia,[a,b,*] **S. Gabici,**[c] **F. A. Aharonian**[d,e] **and J. Vink**[f,g,h]

[a] *Department of Physics, University of Torino, via P. Giuria, 1, 10125 Torino, Italy*
[b] *Istituto Nazionale di Fisica Nucleare, via P. Giuria, 1, 10125 Torino, Italy*
[c] *Université de Paris, CNRS, Astroparticule et Cosmologie, F-75006 Paris, France*
[d] *Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland*
[e] *Max-Planck-Institut für Kernphysik, Postfach 103980, D-69029 Heidelberg, Germany*
[f] *GRAPPA, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
[g] *API, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
[h] *SRON Netherlands Institute for Space Research, Utrecht, The Netherlands*
E-mail: sarah.recchia@unito.it

The cosmic ray electron spectrum exhibits a break at a energy of ~ 1 TeV and extends without any attenuation up to ~ 20 TeV. Energy losses strongly constrain the time of emission of ~ 20 TeV electrons to $\approx 2 \times 10^4$ yr and the distance of the potential source(s) to $\approx 100 - 500$ pc, depending on the cosmic ray diffusion coefficient. This suggests that maybe a single nearby source may dominate the multi-TeV electron spectrum. Here we show that a local source of age $\approx 10^5$ yr, that continuously inject electrons with a fading luminosity (on timescales of $\sim 10^4$ yr), can naturally explain the entire spectrum of cosmic ray electrons in the TeV domain. Despite a nearby pulsar may easily explain the fading profile, the drop of the positron fraction above $\sim 400 - 500$ GeV, make such scenario problematic. Supernova remnants accelerate mostly electrons, rather than positrons, but they can hardly provide a fading injection. A third class of potential are stellar wind shocks, which however are likely to have a constant luminosity on timescales $>> 10$ kyr and probably cannot match the time requirement of our potential source. Therefore, the identification of the potential source(s) of multi-TeV electrons probably requires a profound revision of the present paradigms of acceleration and escape in such objects.

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1. Introduction

In the last years the cosmic ray (CR) electron spectrum has been measured up to multi-TeV energies and two interesting features have emerged: i) the presence of a pronounced break at $\sim$ 1 TeV [1–4]; ii) the spectrum appears to extend up to $\sim$ 20 TeV without a visible cut-off [1].

The detection of multi-TeV electrons poses serious constraints on the distance and age of the potential sources. Indeed such particles undergo severe energy losses in the interstellar medium (ISM), mainly due to inverse Compton scattering on the interstellar radiation field and synchrotron cooling on the Galactic magnetic field. In the standard scenario of diffusive Galactic CR propagation and with typical values of the interstellar CR diffusion coefficient, the maximum age and distance of the potential electron TeVatrons is about $\approx 10^5$ yr and $\approx 100-500$ pc (see e.g [5, 6]).

Such rather strict limitations also poses the question on the number of astrophysical sources that may actually contribute to the TeV electron flux. Indeed it is quite plausible that very few local sources, or even only one source, may dominate the multi-TeV electron spectrum. Instead, at lower energies, energy losses are less severe and also distant sources can contribute.

An other important constraint to the possible source(s) of TeV electrons comes from the measured positron fraction ([7–9]), which is observed to grow in the energy range $\sim 10-200$ GeV, then flattens to a value of ~ 0.15 at ~ 200 GeV [9], and drops above $\gtrsim 400-500$ GeV [10]. The rise of the positron fraction cannot be explained with secondary CR production and additional sources electrons/positrons are needed, such as pulsars, which have been widely identified as possible anti-matter factories (see e.g [11] for a review). On the other hand, the drop of the positron fraction above $\gtrsim 400-500$ GeV suggests that, whatever the electron TeVatrons may be, they should produce preferentially electrons over positrons.

Here we explore a minimal scenario for the interpretation of the Multi-TeV electron spectrum, in which, following the approach by [5, 12], we consider separately the flux from distant sources (beyond $\sim$ 500 pc from Earth), and the contribution of a local electron TeVatron. For the former, we consider a continuous, stationary and homogeneous distribution of sources. For the latter we model in detail the possible time-dependent injection of electrons. In particular we consider the three scenarios of a burst-like source and of a continuous injection over an extended time and with a luminosity that decreases with time (namely a fading source).

We show that the multi-TeV electron spectrum can be well described by a fading electron TeVatron. In this scenario the break at $\sim$ 1 TeV is interpreted as the energy at which the loss time equals the age of the source, while the spectrum above the break is explained by the fading stage of the source.

We conclude with a critical analysis of the type of sources that may be characterized by such fading injection of particles and that are likely to produce mostly electrons over positrons.

2. Mathematical model

The propagation of CR electrons in the ISM is described by the transport equation (e.g. [13])

$$\frac{\partial f(t,\vec{r},E)}{\partial t} - D(E)\vec{\nabla}^2 f(t,\vec{r},E) + \frac{\partial}{\partial E}\left(b(E)f(t,\vec{r},E)\right) = Q(t,\vec{r},E), \tag{1}$$

where $f(t,\vec{r},E)$ is the electron distribution function, E is the particle energy, $D(E)$ is the diffusion coefficient, $b(E)$ is the energy loss rate and $Q(t,\vec{r},E)$ is the injection spectrum. We assume a uniform and isotropic, energy depended diffusion coefficient, parametrized as $D = D_0\ (E/\mathrm{GeV})^{\delta}$, with $D_0 \approx 10^{28}$ cm^2/s and $\delta \sim 0.3-0.6$ as inferred from current models of Galactic CR propagation (see e.g. [14, 15]). The energy loss rate is mainly due to ionization/Coulomb losses (dominant at low energies), Bremsstrahlung (dominant at intermediate energies) and synchrotron/inverse Compton scattering (dominant at high energies). Following [5], we model energy losses as:

$$\frac{\mathrm{d}E}{\mathrm{d}t} \sim a_i + a_B\left(\frac{E}{\mathrm{TeV}}\right) + a_{s/C}\left(\frac{E}{\mathrm{TeV}}\right)^2, \tag{2}$$

where $a_i \approx 10^{-7}(n/\mathrm{cm}^{-3})$ eV/s describes the ionization losses in a ISM of density $n = 1$ cm^{-3}, $a_B \approx 7\times10^{-4}(n/\mathrm{cm}^{-3})$ eV/s the Bremsstrahlung energy losses, and $a_{s/C} \approx 0.1\ (w/\mathrm{eV\ cm}^{-3})$ eV/s the synchrotron and inverse Compton energy losses, with $w \approx w_B + w_{CMB} \approx 1$ eV/cm^3 representing the sum of the energy density of target photons (we consider mostly CMB photons, since optical-IR photons affect the energy losses only in a rather small energy range) and the Galactic magnetic field.

For 20 TeV electrons this implies a loss time of $t_l(20\ \mathrm{TeV}) \sim 2\times10^4(w/\mathrm{eV\ cm}^{-3})^{-1}$ yr, and a source distance of $\approx 100-500$ pc. Moreover, if we interpret the spectral break $E_{br} \sim 1$ TeV as a cooling break, we can immediately estimate the source age as $t_a = t_l(E_{br})$, namely

$$t_a \sim 3\times10^5\left(\frac{w}{\mathrm{eV/cm}^3}\right)^{-1}\ \mathrm{yr}. \tag{3}$$

2.1 Local source

We consider a source located at $\vec{r}_s = 0$ that injects electrons with a power-law spectrum $S(E) = S_0(E/\mathrm{TeV})^{-\alpha}$ and with different temporal injection patterns. In particular we investigate a burst-like and a continuous (fading) injection.

2.1.1 Burst-like source

The injection term is in the form $Q(t,\vec{r},E) = S(E)\delta(t)\delta(\vec{r})$. The solution of the transport equation (Eq. 1) is [5]:

$$f(t_a,\vec{r},E) = \frac{S(E_{t_a})}{\pi^{3/2}r_d^3(E,E_{t_a})}\frac{b(E_{t_a})}{b(E)}\exp\left[-\frac{\vec{r}^2}{r_d^2(E,E_{t_a})}\right] \tag{4}$$

$$t_a = \int_E^{E_{t_a}}\frac{dE'}{b(E')} \approx \frac{E\ E_{br}(t_a)}{E+E_{br}(t_a)}$$

$$r_d^2(E,E_{t_a}) \equiv 4\int_E^{E_{t_a}}\frac{D(E')}{b(E')}dE' \approx 4\,D(E)\,t_E.$$

Electrons of energy E_{t_a} cool down to energy E during a time t_a and r_d represents the diffusion length. The approximation for such quantities have been obtained in the multi-TeV energy range, where synchrotron and inverse Compton losses dominate. The break energy is given by $E_{br}(t_a) = \frac{1}{a_{s/C}t_a}$, and $t_E = min\left(t_a, \frac{1}{a_{s/C}E}\right)$. An typical burst-like source solution is shown in Fig. 1. For a source age $t_a = \frac{1}{a_{s/C}E_{br}}$ corresponds to $E_{br} \sim 1$ TeV. This gives $t_a \approx 10^5$ yr. At energies larger than E_{br}

the cooling time is shorter than the age of the source and such particles cannot reach the observer. This results in a sharp cutoff in the spectrum. Thus it is not possible to reproduce with a single burst-like source both the spectral feature at $E \sim 1$ TeV and the spectrum up to ~ 20 TeV.

It is still interesting for the following discussion to estimate the total energy that such source should inject in electrons in order to reproduce the ~ 1 TeV break. By fitting $f(t_a, E)$ to the DAMPE data ($\approx 4 \times 10^{-6}$ eV/cm^3) at $E = E_{br}$, for a $\alpha = 2$ spectrum, we get $W_b \approx 7 \times 10^{48}$erg, a value somewhat larger than that expected for electrons from SNRs.

2.1.2 Continuous source

We consider a source located at $\vec{r}_s = 0$, that turned on at time 0 and continuously injected electrons with a power-law spectrum $S(E) = S_0(E/\mathrm{TeV})^{-\alpha}$ up to the present time t_a. The source luminosity $L(t)$ is assumed to decrease with time. The injection term is given by $Q(t, \vec{r}, E) = S(E)L(t)H(t_a)\delta(\vec{r})$,. The solution of the transport equation, (Eq. 1), reads [5]:

$$f(t_a, \vec{r}, E) = \int_0^{t_a} dt' \frac{S(E_{t'})L(t')}{\pi^{3/2} r_d^3(E, E_{t'})} \frac{b(E_{t'})}{b(E)} e^{-\frac{\vec{r}^2}{r_d^2(E, E_{t'})}}. \tag{5}$$

The case of a fading source is somewhat intermediate between that of a burst-like and a constant luminosity source. Let us consider, for instance, a time dependence of the luminosity in the form $L(t) = \frac{L_0}{[1+\frac{t}{\tau}]^\gamma}$, with $\gamma > 0$. If τ/t_a is small ($\lesssim 0.01$) or γ is large ($\gtrsim 3$), the source releases most of electrons in a short time compared to the source age, which gives a solution similar to a burst-like source. In the opposite case we recover a solution close to the constant luminosity case. An intermediate case is illustrated in Fig. 1, where we show the result for $\gamma = 2$ and $\tau/t_a \sim 0.05$. The spectrum presents a drop at energy $\approx E_c(t_a) = \frac{1}{a_{s/C} t_a}$, that corresponds to the cooling break of a burst-like source of the same age. The amplitude of the drop depends on τ/t_a and is large (small) if this ratio is small (large). Also other forms of $L(t)$ may be considered. For instance, in Fig. 1 we show the case of $L(t) = L_0 e^{-t/\tau}$ with $\tau/t_a \sim 0.2$, which also agrees, though marginally, with the data.

2.2 Flux from distant sources

Beyond a distance $r_0 \approx 500$ pc from Earth, we assume that sources are distributed homogeneously in the Galactic disc (radius R = 15 kpc and height h = 150 pc), and provide a stationary continuous injection of electrons, with a power-law spectrum with slope and maximum energy ($\alpha = 2.4$, $\mathrm{E_{max}} \gtrsim 10^5$ GeV). The corresponding injection term reads

$$Q(t, \vec{r}, E) = S(E) \exp\left(-\frac{x^2 + y^2}{R^2} - \frac{z^2}{h^2}\right) \quad \text{for } r > r_0 \tag{6}$$

which, substituted in Eq. (1), gives

$$f(\vec{r} = 0, E) = \int_E^\infty dE' \frac{S(E')}{2b(E)} \frac{e^{-\frac{r_0^2}{r_d^2}\left(1+\frac{r_d^2}{R^2}\right)}}{\left(1 + \frac{r_d^2}{R^2}\right)\sqrt{1 + \frac{r_d^2}{h^2}}}. \tag{7}$$

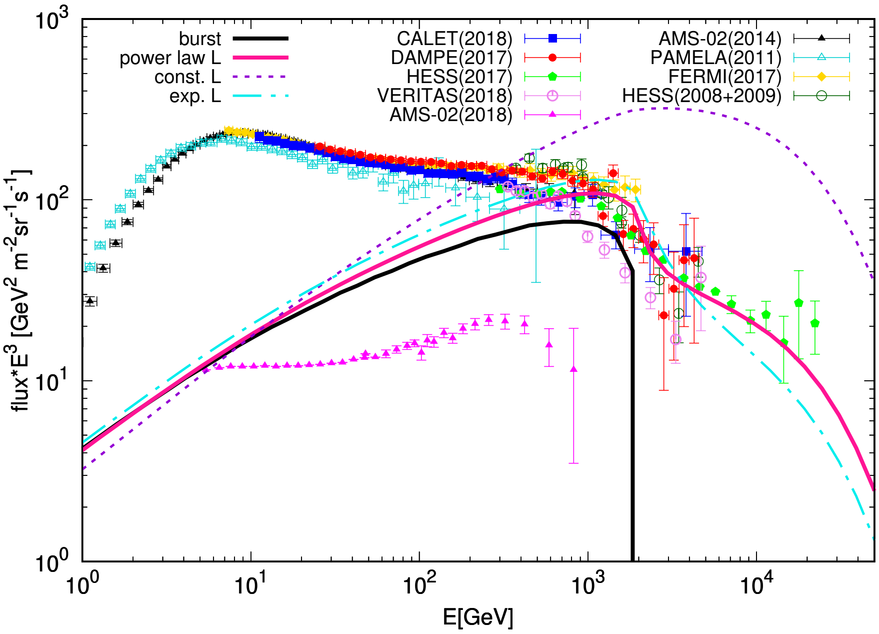

Figure 1: Examples of electron spectra from a single point source, in the case of different types of injection: burst-like (black solid line), $L(t) = L_0/\left[1+\frac{t}{\tau}\right]^2$ (magenta solid line, $\tau/t_a \sim 0.05$), constant luminosity (purple dashed line), $L(t) = L_0 e^{-t/\tau}$ (cyan dot-dashed line, $\tau/t_a \sim 0.2$). In all cases: D(E) = 10^{28}(E/10 GeV)$^{0.3}$ cm^2/s, α = 2.3, $t_a = 10^5$ yr, d = 100 pc. Data points are from [1–3, 16–20].

The contribution from distant sources dominates the observed flux below ≈ 100 GeV. Indeed, above that energy, losses prevent particles produced beyond ≈ r_d to reach the observer, namely at ∼ 100 GeV $r_d = \sqrt{D\, t_l} \approx 500$ pc. At larger energies the contribution from the local source emerges. This can be seen in Fig. 2.

3. Comparison with the data

We have shown that a single fading local source can reproduce both the 1 TeV break and the electron spectrum in the multi-TeV energy range. In Fig. 2 we present a qualitative fit to the electron spectrum, obtained by adding the contribution of the local source and that of distant sources. For distant sources we assume a luminosity ≈ 1.5×10^{39} erg/s, which corresponds to an electron injection rate between 1.5 − 5% of the total CR injection rate in the Galaxy. For the local source we assume $t_a \sim 10^5$ yr, d = 100 pc, $\tau/t_a \sim 0.08$, $\gamma = 2$, $\alpha = 2.3$, and a total energy ≈ 4×10^{47} erg). Such energy input corresponds to ∼ 0.4% of the total energy in CRs expected to be injected by a SNR (≈ 10^{50} erg). Interestingly, if one assumes that the local source also produces CR protons with a total energy ∼ 100 times than that in electrons, namely 4×10^{49} erg, the flux of the local source would be subdominant compared to the observed one (see also Fig. 2 of [21]). The diffusion coefficient is assumed as D(10 GeV) ∼ 10^{28} cm^2/s and $\delta = 0.3$, but larger slopes (up to ∼ 0.6) for the diffusion coefficient are also in agreement with data [15]. In the proposed scenario, distant sources dominate the electron spectrum below ≈ 100 GeV. Above that energy the local source starts to dominate. Above ≈ 1 TeV a qualitatively good agreement with the data is

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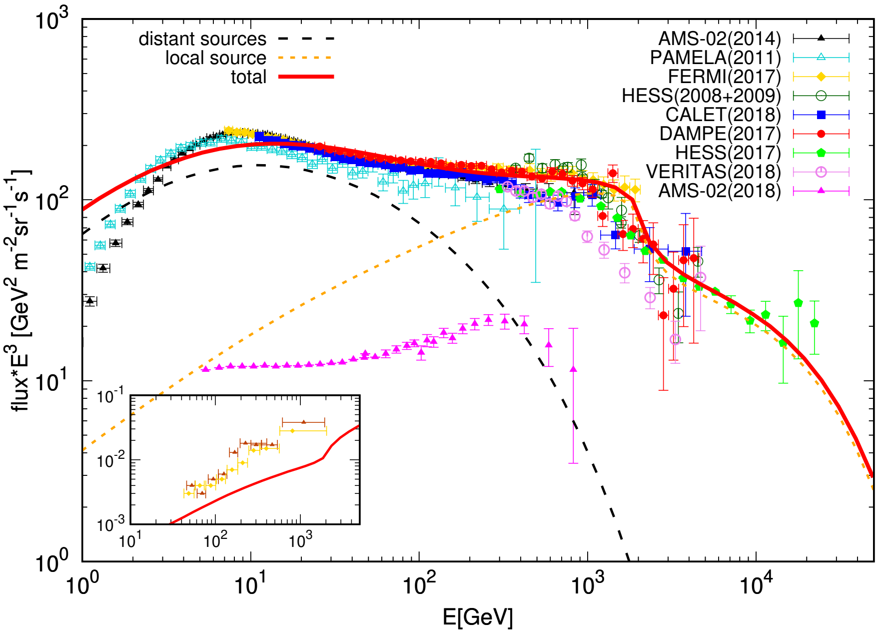

Figure 2: Possible fit to the total observed electron spectrum for D(E) = 10^{28}(E/10 GeV)$^{0.3}$ cm^2/s, due to distant sources (beyond 500 pc, α = 2.4)and a local continuous fading source (α = 2.3, d = 100 pc, t_a = 10^5 yr, τ/t_a = 0.08). The positron flux is also shown (magenta points) [10]. The inset shows the measured upper limits [22] for the anisotropy compared with our predictions.

obtained. Indeed, datasets from different experiments above TeV are quite different. However, our fading source scenario is robust and can reproduce the data without requiring very specific values of the parameters. For instance, a good fit may be obtained by varying the injection spectrum of the local source, $\alpha \approx 1.8...2.4$, or the diffusion coefficient, $\delta \approx 0.3...0.6$. The $L(t)$ chosen to describe the fading of the source provides a reasonably good fit of the data for parameters in the range $2 < \gamma < 3$ and $\tau/t_a \approx 0.01...0.1$. A lower value of γ requires a correspondingly lower value of τ/t_a. In the present scenario, the dipole anisotropy in the arrival direction of particles is determined for the local source as: $a = (3D(E)/c)|\nabla f_s|/f_{tot}$ where f_s is the flux corresponding to the local source and f_{tot} is the total electron flux [13]. In Fig. 2 we compare this estimate with the upper limits provided by Fermi [22], showing that the estimated anisotropy is below the upper limits.

4. Discussion and conclusions

We demonstrate that a single local fading source of electrons, with age $\approx$ 100 kyr and fading timescale of $\tau \approx$ 10 kyr, can naturally reproduce the multi-TeV electron flux. On the other hand, a burst-like or a constant luminosity injection would fail in reproducing observations. Our conclusions are robust and poses a serious question on the possible nature of such source. In fact, a fading profile would be naturally explained by a pulsar, but, at least in the standard paradigm of electron/positron acceleration in pulsars, an equal amount of electrons and positrons should be produced, which is excluded by data. From the energetic point of view, both SNRs and and powerful winds from massive Wolf-Rayet stars [23] may be a candidate for a local source. The problem is whether such sources could provide the temporal fading pattern required to fit the electron spectrum. Indeed, $\tau \approx 10$ kyr is definitely shorter than the duration of the Sedov phase of a SNR, and it is surely possible that a SNR may accelerate multi-TeV electrons over such a time scale [24]. However, it is not clear whether such particles can escape the accelerator during the acceleration process (see e.g. [25]), such as to produce the required fading pattern. As for stellar winds, it could be even more difficult to explain a fading pattern over a timescale of 10 kyr, since such objects might inject continuously with nearly constant luminosity on timescales >> 10 kyr. Thus, the identification of the potential source(s) of multi-TeV electrons requires to carefully reconsider what we do know about the possible particle accelerators.

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