

Anisotropies in the flux of cosmic ray electrons and positrons

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Abstract. High energy cosmic ray electrons and positrons probe the local properties of our galaxy. In fact, regardless of the production mechanism, electromagnetic energy losses limit the typical propagation scale of GeV-TeV electrons and positrons to a few kpc. In the diffusion model, the presence of nearby and dominant sources may produce an observable dipole anisotropy in the cosmic ray fluxes. We present a detailed study on the role of anisotropies from nearby sources in the interpretation of present cosmic ray electron and positrons fluxes. Predictions for the dipole anisotropy from known astrophysical sources as Supernova Remnants (SNRs) and pulsars taken from the Green and the Australia Telescope National Facility (ATNF) catalogs are shown. The results are obtained from models compatible with the most recent AMS-02 data on electrons and positrons fluxes. In particular, anisotropies for single sources as well as for a distribution of catalog sources are discussed. We compare our results with current anisotropy upper limits from the Fermi-LAT and PAMELA experiments, showing that the search of anisotropy in the electron and positron fluxes represents a complementary tool to inspect the properties of close SNRs, as for example the Vela SNR.

1. Introduction

In the last years, the fluxes of electrons and positrons in Cosmic Rays (CRs) have been measured with high precision by the AMS-02 [1, 2], *Fermi*-LAT [3] and PAMELA [4] experiments. The observed fluxes can be interpreted as the emission from a variety of astrophysical sources, as for example Supernova Remnants (SNRs), Pulsar Wind Nebulae (PWNe) and the spallation of primary CRs in the interstellar medium, see *e.g.* [5]. Also, the detected fluxes have been analyzed in terms of anisotropies in their arrival directions. Searches for anisotropies in the electron plus positron flux [6], the positron to electron ratio [1] and the positron flux [7] have been presented respectively from the *Fermi*-LAT, AMS-02 and PAMELA experiments, all ending up with upper limits on the dipole anisotropy. In this work we show how the search for anisotropies in the electron and positron fluxes at GeV-TeV energies can be an interesting tool, in addition to the measured fluxes, to study the properties of near sources, as for example near SNRs.

2. Modeling the electron and positron fluxes

Electron and positron production in our galaxy is possible through different processes. *Primary* electrons can be accelerated with Fermi non relativistic shocks up to high energies in SNRs



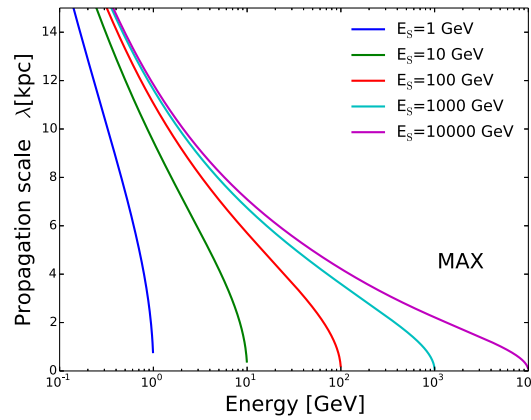


Figure 1. Propagation scale λ for electrons and positrons in our galaxy as a function of the energy at Earth, for different energies at source E_s and adopting the MAX propagation model.

[8]. In addition, both electrons and positrons are created in the strong magnetic fields that surround pulsars and then accelerated with relativistic shocks in the PWN [9]. A source of *secondary* electrons and positrons is the fragmentation of primary CR nuclei in the interstellar medium material (hydrogen, helium). Independent of the production mechanism, electrons and positrons propagate in the Galaxy and are affected by a number of processes. Above a few GeV, the propagation is dominated by the diffusion in the interstellar magnetic field irregularities and by energy losses, which are due to inverse Compton scattering on ambient photons and to synchrotron emission. This is typically described by a diffusion equation for the number density $\psi = \psi(E, \mathbf{x}, t) \equiv dn/dE$ per unit volume and energy:

$$\frac{\partial \psi}{\partial t} - \nabla \cdot \{K(E) \nabla \psi\} + \frac{\partial}{\partial E} \left\{ \frac{dE}{dt} \psi \right\} = Q(E, \mathbf{x}, t) \quad (1)$$

where $K(E) = K_0 E^\delta$ is the energy dependent diffusion coefficient, the dE/dt term accounts for the energy losses and $Q(E, \mathbf{x}, t)$ includes all the possible sources. In this work a semi analytical approach is followed to solve the diffusion equation in Eq. 1 for each source, as fully detailed in [10, 11]. Within this approach, the Galaxy is modeled as a cylinder of radius $r_{\text{disc}} = 20$ kpc and half height L . The parameters K_0, δ, L are usually constrained from boron over carbon ratio (B/C). In particular, in the following we show results for the MAX benchmark model derived in [12]. At high energies ($E > 10$ GeV) the electrons and positrons that we observe are probes of the local Galaxy. In fact, for leptons the energy loss timescale is smaller than the diffusion timescale. This can be visualized in Fig. 1, where the typical propagation scale λ as a function of the energy at Earth is plotted for different values of the energy at source E_s and for the MAX propagation model. We see that λ for GeV-TeV electrons and positrons is less than ~ 5 kpc for the different E_s considered. The interpretation of high energy electrons and positrons is thus connected to the inspection of local sources. The chosen modeling of electron and positron sources is functional to this aim, and is based on [11, 10, 5]. We remind here only the principal characteristics of this modeling. We include both single SNRs and PWNe, whose characteristics are taken directly from the existing catalog, and a distribution of SNRs, described by average characteristics. The secondary component is taken from [5]. The spatial distribution of SNRs is modeled with a smooth distribution of sources active beyond a radius R_{cut} from the Earth (*far* SNRs), and following the radial profile derived in [13]. Instead, single

sources taken directly from the Green Catalog [14] are considered for $R \leq R_{\text{cut}}$ (*near* SNR). To inspect the role of single near SNRs we consider $R_{\text{cut}} = 0, 0.7$ kpc. The PWNe component is computed taking from the ATNF catalog [15] the sources with ages $50 \text{ kyr} < t_{\text{obs}} < 10000 \text{ kyr}$. In fact, the release of the accelerated $e^\pm$ pairs is estimated to start at least after $40 - 50$ kyr after the pulsar birth [9]. The energy injection spectrum $Q(E)$ for both SNR and PWN is

$$Q(E) = Q_0 \left(\frac{E}{E_0} \right)^{-\gamma} \exp \left(-\frac{E}{E_c} \right) \quad (2)$$

where $E_c = 5$ TeV is the cutoff energy and $E_0 = 1$ GeV. The index of the energy spectrum is expected to be different for particles accelerated in SNRs ($\sim 2 - 2.5$) and PWNe (< 2). The normalization of this spectrum is constrained using catalog quantities for single SNRs and PWNe, while using average population characteristics for the smooth SNR component. For example, the normalization for a single PWN is obtained supposing that a fraction η of the spindown energy of the pulsar W_0 is emitted in form of $e^\pm$ pairs. The normalization for a single SNR is constrained with radio and catalog data, as for example the radio flux, the distance and magnetic field of the remnant (see Eq. 50 in [10]). As for the smooth SNR distribution, this can be connected to average Galactic characteristics, as for example the mean energy released in electrons per century $E_{\text{tot,SNR}}$.

2.1. Anisotropy

As shown in Fig. 1, CR electrons and positrons with observed energies in GeV-TeV range originated from relatively nearby locations in the Galaxy. This means that it could be possible that such high energy electrons originate from a highly anisotropic collection of nearby sources. Under this hypothesis, even after the diffusive propagation in the Galactic magnetic field is taken into account, a residual small dipole anisotropy should be present in the observed fluxes. In the assumption of one or few nearby sources dominating the CR flux at Earth, the dipole anisotropy is usually defined as

$$\Delta = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \quad (3)$$

being I_{max} (I_{min}) the maximum (minimum) CR intensity values. In a diffusive propagation regime this can be computed as $\Delta = \frac{3K}{c} \left| \frac{\nabla \psi}{\psi} \right|$ (see [16]), where K is the diffusion coefficient and ψ is the solution to Eq. 1. For example, the anisotropy for a single source of electrons and positrons in our model is computed as

$$\Delta(E)_{e^+ + e^-} = \frac{3K(E)}{c} \frac{2d_s}{\lambda^2(E, E_s)} \frac{\psi_{e^+ + e^-}^s(E)}{\psi_{e^+ + e^-}^{\text{tot}}(E)}, \quad (4)$$

where d_s is the distance to the source, λ is the propagation scale, $\psi_{e^+ + e^-}^s(E)$ is the source $e^+ + e^-$ number density, $\psi_{e^+ + e^-}^{\text{tot}}(E)$ is the total $e^+ + e^-$ number density given by the contributions of all the sources, both isotropic and single sources. Moreover, if a collection of electron and/or positron sources is present, the intensity of the CR flux as a function of direction in the sky $\mathbf{n}$ is (see [17])

$$I(E, \mathbf{n}) = \frac{c}{4\pi} \sum_i \psi_i(E) (1 + \Delta_i \mathbf{n} \cdot \mathbf{r}_i / r_i) \quad (5)$$

where the index i runs over all the sources at position $\mathbf{r}_i$ with electron and/or positron number density $\psi_i(E)$, $\Delta_i = \frac{3K(E)}{c} \left| \frac{\nabla \psi_i(E)}{\psi_i(E)} \right|$, and the total dipole anisotropy is computed directly by means of Eq. 3. To compare our prediction with the present upper limits we compute the integrated dipole anisotropies as a function of the minimum energy. We integrate fluxes in Eq. 4 up to 5 TeV.

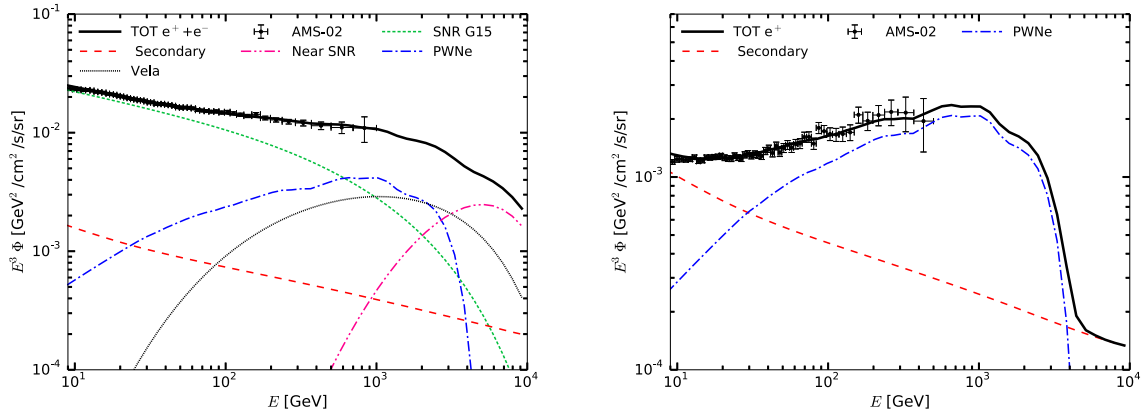


Figure 2. Best fit to $e^+ + e^-$ (left panel) and e^+ (right panel) AMS-02 data [18, 19] for the model with $R_{\text{cut}} = 0.7$ kpc described in Sec. 3 and MAX propagation setup. Solid black: sum of all the plotted components; red dashed: secondary $e^+ + e^-$ (left panel) and e^+ (right panel); blue dash-dotted: $e^+ + e^-$ (left panel) and e^+ (right panel) from the collection of PWNe in the ATNF catalog; green dotted: e^- from the far SNR distribution with $R_{\text{cut}} = 0.7$ kpc; black dotted: e^- for the Vela SNR; magenta double dash-dotted: e^- from the near SNRs in the Green Catalog with $R \leq 0.7$ kpc.

3. Results and Conclusions

The aim of this analysis is to provide dipole anisotropies predictions for models compatible with the observed electron and positron fluxes. Therefore, each model is fitted to the AMS-02 data on the e^+ [18] and $e^+ + e^-$ [19] fluxes. The models are fitted to the data starting from $E = 10$ GeV. This choice minimizes the effect of the solar modulation of fluxes, that is however taken into account with a modulation potential ϕ_F , according to the force field approximation. The inspected models differ mainly for the treatment of the contribution from local sources. As an example, two models and the corresponding predictions for anisotropies are discussed here.

With the first model we aim to analyze the role of single near SNRs (in particular the Vela SNR) in the high energy flux and, consequently, in the electron plus positron anisotropy. Fluxes are fitted considering a secondary component, the contribution from single PWNe in the ATNF catalog, a smooth distribution of SNRs with $R_{\text{cut}} = 0.7$ kpc, the contribution from single near SNRs in the Green catalog with $R \leq R_{\text{cut}}$. Among the near SNRs, Vela is treated separately from the other sources as detailed in [11]. For this analysis, its spectral index is fixed to $\gamma = 2.5$, its distance to 0.293 kpc and its age to 11.4 kyr. The results of our fit are presented in Fig. 2. A number of free parameters is used to fit our model to the data. This includes a normalization for the secondary component, a common spectral index and efficiency η for all the PWNe, a normalization for the *near* component, the magnetic field for the Vela SNR, and a spectral index and a free normalization for the smooth SNR distribution. More details on the fit parameters are given in [11]. The fit to the AMS-02 fluxes is remarkably good, with a reduced $\chi^2/\text{d.o.f.} = 38/89$. The role of near SNR, in particular Vela, in shaping the $e^+ + e^-$ fluxes (left panel) is evident for $E \gtrsim 300$ GeV. We thus compute the corresponding dipole anisotropy for the Vela SNR and for the Cygnus Loop, which dominates the contribution of the near SNRs with $R < R_{\text{cut}} = 0.7$ kpc. In Fig. 3 (left panel) the integrated $e^+ + e^-$ anisotropy as a function of the minimum energy E_{min} for Vela and Cygnus Loop of the model in Fig. 2 are shown. The arrows correspond to the *Fermi*-LAT upper limits in [6]. The predicted anisotropies grow with E_{min} and reach the maximum value of $\Delta_{e^+ + e^-} = 0.04$ for the Vela SNR and 0.15 for Cygnus Loop at TeV minimum

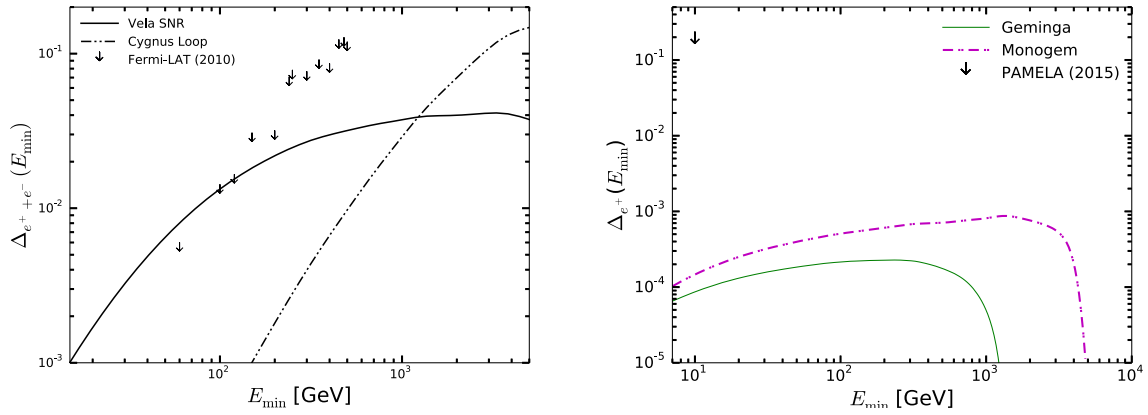


Figure 3. Left panel: predictions for the dipole anisotropies in the $e^+ + e^-$ flux for the Vela SNR (solid) and the Cygnus Loop (dot-dashed) as a function of the minimum energy for the model with $R_{\text{cut}} = 0.7$ kpc. The arrows correspond to the *Fermi*-LAT upper limits [6]. Right panel: prediction for the dipole anisotropies in the e^+ flux for the Geminga (green solid) and Monogem (magenta dot-dashed) PWNe as a function of the minimum energy for the model with $R_{\text{cut}} = 0$ kpc. The arrow corresponds to the PAMELA upper limit in [7].

energies. For $E_{\min}$ below about 150 GeV the upper limits are at the same level of the prediction for the Vela anisotropy. Thus, present *Fermi*-LAT upper limits start to test some of the models (see also [11]) for the Vela SNR that are compatible with the flux data. Future results from the full statistics of *Fermi*-LAT data, as well as ongoing experiments such as DAMPE and CALET [20], will improve the potentiality for the anisotropy to explore and eventually exclude some of the models that explains the $e^\pm$ fluxes. To explore the role of all the collection of sources in this model, we show in Fig. 4 the interstellar intensity of the $e^+ + e^-$ flux as a function of the direction in the sky in Galactic coordinates for growing minimum energies. The result obtained with Eq. 5 is shown by means of its percentage difference between the mean intensity from the entire source collection. The maximum of the intensity (yellow dot) is found to be a direction very close to Vela (black dot) for $E_{\min} = 126$ and $E_{\min} = 661$ GeV (top panels). At higher energies, the interplay between the Vela, Cygnus Loop and the other sources shifts the maximal intensity in direction of Cygnus Loop (bottom panels).

The second model aims to analyze the role of the most powerful PWNe among our collection of ATNF sources and, in particular, the resulting positron anisotropy. The difference with the previous model is that we consider a smooth distribution of SNRs all over the Galaxy, thus $R_{\text{cut}} = 0$ kpc, and none of the SNRs in the Green catalog. Therefore, the only single sources are the PWNe. For example Geminga and Monogem PWN, for which we present Fig. 3 (right panel) the integrated dipole anisotropies in the e^+ flux, together with the upper limit obtained with PAMELA data in [7]. The maximum anisotropy is given by the Monogem PWN at about 1 TeV. Geminga gives a lower anisotropy due to its age (343 kyr vs. 111 kyr for Monogem, see discussion in [11]). The predicted anisotropy is more than three orders of magnitude below the Δ_{e^+} upper limit. This gap suggests that likely present or forthcoming data on positron anisotropy will not have the sensitivity to test the properties of ATNF PWNe that explains the AMS-02 data.

To conclude, in this proceeding we have shown how anisotropies in the electron and positron fluxes can be a tool to study the properties of near sources, as for example near SNRs, in addition to high precision measurements of the fluxes.

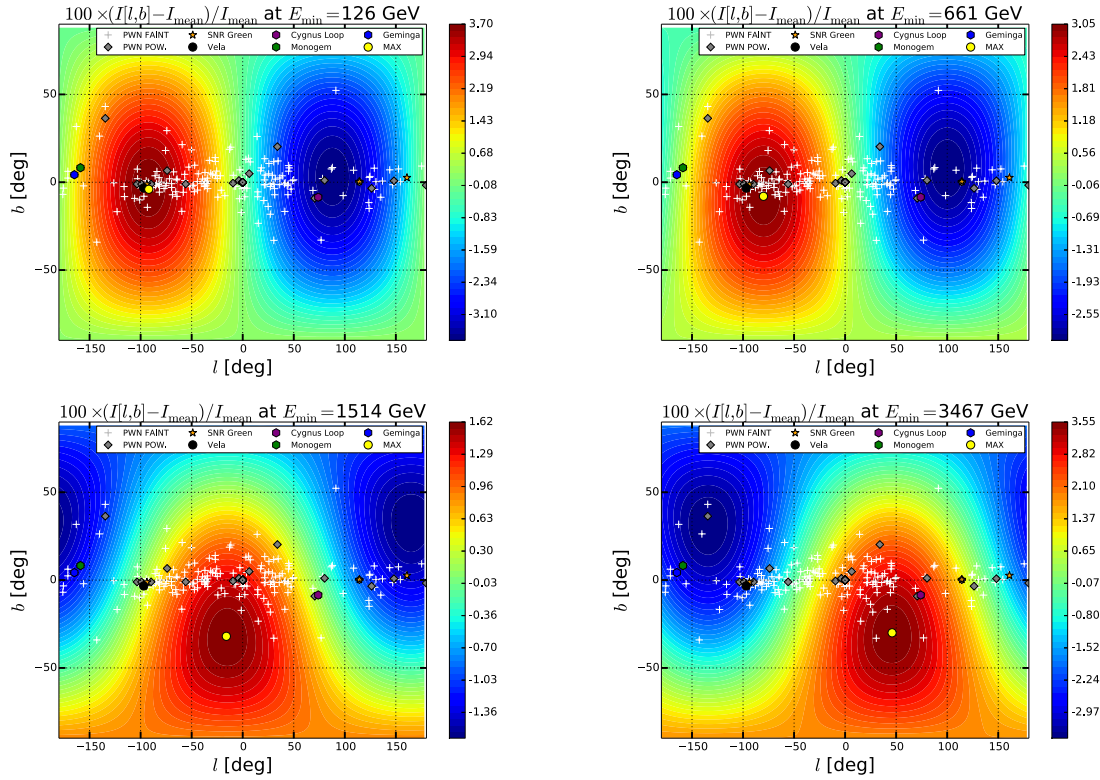


Figure 4. Contour plots of the intensity of the $e^+ + e^-$ flux as a function of the direction in the sky, obtained for all the sources in the model with $R_{\text{cut}} = 0.7$ kpc. The color scale indicates the percentage relative difference between the intensity in a given direction of the sky (l, b) [deg] and the mean intensity computed from the entire source collection. The position of the maximum intensity is highlighted with a yellow dot, while the other symbols indicate the position of the sources. The four panels represent the evolution for increasing minimum energy.

References

- [1] Aguilar M, Alberti G, Alpat B, Alvino *et al.* (AMS Collaboration) 2013 *Phys. Rev. Lett.* **110**(14) 141102
- [2] Accardo L *et al.* (AMS Collaboration) 2014 *Phys. Rev. Lett.* **113**(12) 121101
- [3] Ackermann M, Ajello *et al.* 2012 *Physical Review Letters* **108** 011103 (*Preprint* 1109.0521)
- [4] Adriani O *et al.* 2009 *Nature* **458** 607–609 (*Preprint* 0810.4995)
- [5] Di Mauro M, Donato F, Fornengo N, Lineros R and Vittino A 2014 *JCAP* **4** 006 (*Preprint* 1402.0321)
- [6] Ackermann M *et al.* 2010 *Phys. Rev. D* **82** 092003 (*Preprint* 1008.5119)
- [7] Adriani O *et al.* 2015 *Astrophys. J.* **811** 21 (*Preprint* 1509.06249)
- [8] Blandford R and Eichler D 1987 *Phys. Rept.* **154** 1–75
- [9] Blasi P and Amato E 2011 *Astrophysics and Space Science Proceedings* **21** 624 (*Preprint* 1007.4745)
- [10] Delahaye T, Lavalle J, Lineros R, Donato F and Fornengo N 2010 *A&A* **524** A51 (*Preprint* 1002.1910)
- [11] Manconi S, Di Mauro M and Donato F 2016 *ArXiv e-prints* (*Preprint* 1611.06237)
- [12] Donato F, Fornengo N, Maurin D and Salati P 2004 *Phys. Rev. D* **69** 063501 (*Preprint* astro-ph/0306207)
- [13] Green D A 2015 *MNRAS* **454** 1517–1524 (*Preprint* 1508.02931)
- [14] Green D 2014 *Bull.Astron.Soc.India* **42** 47 (*Preprint* 1409.0637)
- [15] Manchester R N, Hobbs G B, Teoh A and Hobbs M 2005 *AJ* **129** 1993–2006 (*Preprint* astro-ph/0412641)
- [16] Ginzburg V L and Syrovatskii S I 1964
- [17] Shen C S and Mao C Y 1971 *ApJL* **9** 169
- [18] Aguilar M *et al.* 2014 *Physical Review Letters* **113** 121102
- [19] Aguilar M *et al.* 2014 *Physical Review Letters* **113** 221102
- [20] Torii S and CALET Collaboration 2011 *Nuclear Instruments and Methods in Physics Research A* **630** 55–57