33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

Impact of annihilation and triplet pair production on secondary cosmic ray positrons

D. GAGGERO[1,2,3], P.D. SERPICO[3], V. BONNIVARD[3,4]

[1]*SISSA, Via Bonomea 265, 34136 Trieste, Italy*
[2]*INFN, sezione di Trieste, via Valerio 2, I-34127, Trieste, Italy*
[3]*LAPTh, Univ. de Savoie, CNRS, B.P.110, Annecy-le-Vieux F-74941, France*
[4]*Université Joseph Fourier (Grenoble 1), BP 53, 38041 Grenoble Cedex 9, France*

daniele.gaggero@sissa.it *LAPTH-Conf-028/13*

Abstract: Current cosmic ray (CR) experiments are capable of very precise flux measurements. Some of the CR species, like positrons, are used for astrophysical and particle physics diagnostics, hence the assessment of the error on theoretical predictions assumes a particular importance. Here we quantify the role of two typically unaccounted effects on the low and high energy CR positron range: annihilation of sub GeV scale positrons and triplet pair production by TeV-scale leptons in the interstellar medium, respectively. We checked both analytically and numerically (via modifications of the DRAGON code) that the expected effects are safely below the 1% level in the GeV-TeV range of major phenomenological interest. They can thus be neglected for most practical purposes.

Keywords: cosmic ray positrons.

1 Introduction

The cosmic ray (CR) spectrum outside the atmosphere contains small amounts of positrons. These particles mostly originate from collisions of "primary" CRs in the rarefied interstellar medium (ISM); the probability of this process can be inferred from the grammage deduced by other secondary/primary ratios like boron/carbon (B/C). For this reason, positrons are useful to constrain CR propagation and interactions in the ISM as well as to search for primary sources (either astrophysical or exotic from dark matter annihilation/decay) on top of the secondary contribution (see e.g. [1] for a review).

The present generation of space detectors like PAMELA [2] and, most notably, AMS-02 [3], are significantly reducing the measurement errors on CR species, including e^+. To avoid biasing the interpretation of measurements, it is thus mandatory to assess the errors due to simplifications in theoretical predictions and possibly removing them.

Here we discuss two physical processes which are usually neglected in numerical and semi-analytical packages such as `GALPROP` [4], `DRAGON` [5], and `USINE` [6]: positron annihilation $e^+e^- \to \gamma\gamma$ and triplet pair production $e\gamma \to e e^+ e^-$.

We shall quantify the impact of these two processes respectively at (sub-)GeV and (sub-)TeV energies. In both cases, we shall study their impact via a modification of `DRAGON` (see Sec.s 3,4). In the former case, we shall also provide an analytical modeling (Sec. 2). In Sec. 5 we conclude.

2 Semi-analytic model of e^+ annihilation

Thanks to the fact that energy losses for leptons at GeV energies are dominated by scattering onto the gas of the Galactic Disk (via bremsstrahlung and ionization/Coulomb collisions), rather than the diffuse radiation and magnetic fields in the diffusion zone, the e^+ flux can be reasonably estimated in this range via a "modified slab approximation", see e.g. [7].

Consider an "infinite layer" approximation for the Galactic Disk, so that variations in the radial distance along the disk (R) are neglected and only the leading dependence on the height over the Galactic plane, z, is considered. Also, let us assume that diffusion in the halo (of radial size much larger than its height $R \gg H$) is z-independent; that sources and gas (responsible for losses) are confined to a much thinner "plane" of height h, with density of gas n and injection spectrum per unit time $q_0(p)$. We assume that CR freely escape outside H. If one neglects reacceleration and considers steady state, the positron distribution in momentum space f satisfies

$$-D\frac{\partial^2 f}{\partial z^2}+u\frac{\partial f}{\partial z}-\left[\frac{du}{dz}\frac{p}{3}-\left(\frac{dp}{dt}\right)_{\rm loss}h\,\delta(z)\right]\frac{\partial f}{\partial p}=$$
$$q_0(p)\,h\delta(z)-\left\{\Gamma+\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{\rm loss}\right]\right\}h\,\delta(z)\,f\,, \quad (1)$$

where D is the spatial diffusion coefficient, u the bulk velocity of the ISM plasma, the term in parentheses describe energy losses and $\Gamma = \sigma_{\rm ann}\,c\,n$ is the annihilation rate. The above equation can be solved (i.e. reduced to quadratures) with a technique similar to what used e.g. in [8].

We adopt the following fiducial values for the relevant parameters:

- $H = 4\,$kpc
- $h = 200\,$pc.
- $n = 1\,$cm^{-3}
- $D(p) = D_{28}\times 10^{28}\,$cm^{2}s$^{-1}\left(\frac{pc}{1\,\rm GeV}\right)^{\delta}$, with $\delta = 0.5$ and $D_{28} = 3.3$ as fiducial values.

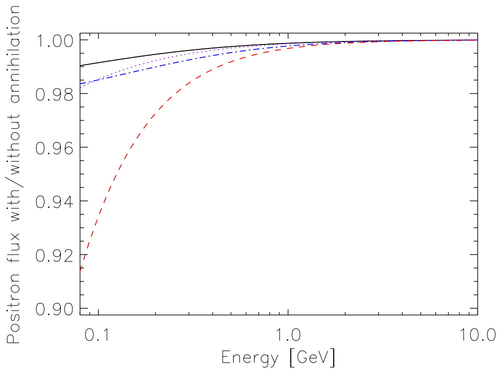

Figure 1: *Ratio of cosmic ray positron flux computed in the toy model accounting for annihilation effects over the case in which they are neglected, in different models: purely diffusive propagation (dashed red); including convection, but no energy losses (dot-dashed blue); including energy losses, but no convection (dotted purple); all effects included (solid, black). See text for parameters and details*

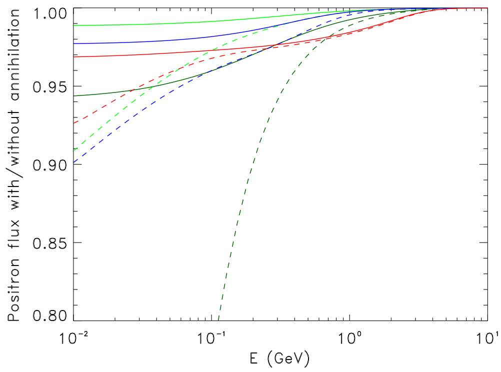

Figure 2: *Ratio of positron flux with/without annihilation computed with* DRAGON*. Dotted lines: without solar modulation; solid lines: with solar modulation. Dark green: simple setup with pure diffusion and no energy losses; other colours: realistic propagation models taken from [12].*

- $u = 20\,\mathrm{km/s} \simeq v_{\mathrm{Alfven}}$.
- $\sigma_{\mathrm{ann}}(p)$ is the well-known annihilation cross section in the relativistic limit [9].
- $q_0(p) = \kappa_+ \left(\frac{pc}{1\,\mathrm{GeV}}\right)^{-4.7}$. Note that since we shall only be interested in either the shape of the solution with respect to the injection (i.e. $f_0(p)/q_0(p)$) or in the ratio of solutions corresponding to different *propagation* parameters, the value of κ_+ is arbitrary and cancels out in the results.
- $\left(\frac{dp}{dt}\right)_\ell$, i.e. the term that accounts for energy losses, is taken from Eq. (4.6.1) in [10] [1], assuming: 1) the ionization rate $x_e = 0.01$; 2) the magnetic field $B = 3\mu G$; 3) the energy density in interstellar light (including CMB), $w = 1\,\mathrm{eV/cm^3}$.

We show in Fig.1 the ratio of positron fluxes computed with/without accounting for annihilation under different assumptions for the propagation. The result suggest that the effect would be significant below the GeV if the propagation were dominated by diffusion (red dashed curve), but the transition to a convection (dot-dashed blue) or a energy-loss dominated (dotted purple) propagation regime makes the overall effect of O(1%) or smaller at sub-GeV energies.

These results have been confirmed in a more complete and physically more realistic implementation of the effect in the DRAGON code, as described in the following section.

3 Positron annihilation: numerical implementation in DRAGON

In order to get a more precise comprehension of the process in different realistic CR propagation scenarios where: **1)** a more detailed model of the Galaxy is considered, and **2)** other relevant effects (e.g. reacceleration) are taken into account, we implemented the CR positron annihilation in DRAGON. This numerical package is designed to solve the complete CR diffusion-loss equation for all nuclear and leptonic species in cylindrical symmetry, adopting a realistic spatial distribution for CR sources, diffusion coefficient, interstellar gas and interstellar radiation field. A more detailed description of the code can be found in [11] and on the official webpage [5].

We implemented the process as a loss term affecting CR positron propagation only; the equations are the generalization of the ones we described in the previous paragraph.

In order to validate the code, we considered a very simple pure diffusion scenario with no reacceleration, no convection, no energy losses and we neglected the effect of solar modulation as well: we found that the suppression of the CR positron flux is negligible above 1 GeV and becomes as large as $\simeq 25\%$ at $\simeq 100$ MeV and $\simeq 85\%$ at $\simeq 10$ MeV, in qualitative accord to what we found with the semi-analytical computation under similar conditions as described in the previous section.

Then, we considered three different propagation setups obtained from the latest analysis on electron, positron and synchrotron spectra performed by the DRAGON team [12]: these realistic scenarios are tuned to fit a large number of CR observables (in particular B/C, protons, antiprotons, electrons, positrons and synchrotron emission). We show in Fig. 2 the suppression of the positron flux with/without the effect of solar modulation. It is clear that the effect is much smaller now: depending on the propagation setup, we get a suppression of $1 \div 3\%$ at 10 MeV on the modulated flux (solid lines), and $7 \div 10\%$ at the same energy on the local interstellar flux (dashed lines). Once again, this is in qualitative accord with what we found with semi-analytical computations, due to the fact that the energy loss mechanisms due to ionization, Coulomb interaction and bremsstrahlung are dominant in the $10 \div 1000$ MeV range.

We can thus conclude that for studies of the positron flux in the GeV range or above this effect can be safely neglected, unless one aims at precision of O(1%) or better. Given current precision, the only instance in which it might be worth accounting for it is in solar modulation studies addressing the charge-dependence of this physical effect, since neglecting the annihilation would amount to introduce a small but *systematic* bias in the estimate of the interstellar positron spectrum (it applies to e^+ but not e^-, of course).

1. Apart for a typo consisting of an extra overall factor 2 included in that reference.

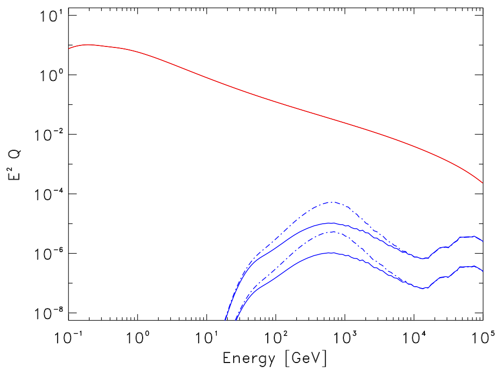

Figure 3: *Source term for secondary positrons of hadronic origin (red solid) compared to the source term for TPP positrons computed under several hypotheses (blue lines). Solid lines: with standard electrons, without/with enhancement in the ISRF. Dotted lines: with a pronounced bump in the electron flux above 1 TeV, without/with enhencement in the ISRF.*

4 Triplet pair production

Another effect which is not taken into account in CR numerical and semi-analyitical codes is the *triplet pair production* (TPP), i.e. the creation of e^+e^- pairs by high energy CR electrons interacting with the diffuse soft photons of the interstellar radiation field (ISRF). As noticed in [13] this process is an unavoidable source of high energy positrons from a pure electron population: TeV electrons interacting with UV diffuse photons ($\varepsilon \sim 10$ eV) give rise to $e^\pm$ pairs with energy $E_{pair} \sim 0.5(E_e/\varepsilon)^{1/2} m_e c^2 \sim 100$ GeV, i.e. within the range which has been now started to be explored in more details by AMS-02 [14].

The TPP was deeply investigated in [15], [16] and more recently [17]: it is a third-order QED process with a very complicated analytical expression for the total differential cross section. We implemented an approximated expression of the cross section: in this paragraph we will briefly describe our implementation and discuss how relevant this process may be as a positron source with resonable assumptions on the TeV electron flux and a realistic model of the ISRF.

The single differential cross section for pair production that we considered is:

$$\frac{d\sigma_{TPP}}{dE_{e^+}} \simeq \sigma_T \,\alpha\, \delta(E_{e^+} - \langle E_{e^+} \rangle)\, g(s) \qquad (2)$$

In this expression σ_T is the Thompson cross section, α is the fine structure constant. The spectrum of secondary positrons is approximated as a delta function centered on $\langle E_{e^+} \rangle = \frac{1}{2} m_e c^2 \sqrt{E_{e^-}/E_\gamma}$. $g(s)$ is a corrective factor derived in [15] and refined in [17], function of the total energy in the center of mass $\sqrt{s}$, and introduced in order to reproduce the correct behaviour of the total cross section with energy.

Actually, in order to assess the importance of this process for the positron flux, it is not necessary to include it in a propagation model. Since it consists of a new source term for e^+, a simple estimate amounts to comparing the additional source function:

$$Q_{TPP}(E_{e^+}) = \int dE_\gamma \int dE_e \, \frac{d\sigma_{TPP}}{dE_{e^+}}(E_{e^+}, E_e, E_\gamma) \frac{dn_\gamma}{dE_\gamma}(E_\gamma)\, c\, \Phi_e(E_e)\,, \qquad (3)$$

with the traditionally considered source function originating from hadronic processes between CRs and ISM medium nuclei:

$$Q_{pp}(E_+) = \int dE_p \frac{d\sigma_{pp}}{dE_+}(E_+, E_p)\, n_g\, c\, \Phi_p(E_p)\,, \qquad (4)$$

with obvious meaning for the symbols.

On the light of present knowledge which strongly suggests that the latter is sub-leading with respect to *primary* positron sources (see e.g. [1]), proving that Eq. (3) is much smaller than Eq. (4) determines *a fortiori* that the overall role of ISM production via TPP is small.

The result is plotted in Fig. 3 and clearly confirms our hypothesis: the conventional source function is larger than the TPP term by more than 2 orders of magnitude in a wide energy range even under very optimisic assumptions on the ISRF and primary electron flux.

5 Conclusions

We have checked both analytically and numerically that a couple of processes usually neglected in theoretical predictions of e^+ fluxes and positron fraction are not important (at the percent level) in the most interesting region between 1 GeV and 1 TeV. Below the former energy, where (charge dependent) modulation effects are important, some role is expected.

For the TPP, ISM production is subleading, and one has to worry only of a possible production near the sources, provided that a high density of optical/UV seed photons is available and e^- (and/or e^+) are accelerated to sufficiently high energies. This case should however be considered as a further possibility of primary source of positrons rather than a contribution to the production during ISM propagation discussed here.

6 Acknowledgements

DG warmly thanks the LAPTh for hosting and financial support during the realization of this project.

References

[1] P. D. Serpico, Astropart. Phys. **39-40**, 2 (2012) [arXiv:1108.4827 [astro-ph.HE]].
[2] `http://pamela.roma2.infn.it/index.php`
[3] `http://ams.cern.ch/`
[4] `http://galprop.stanford.edu/`
[5] `http://dragon.hepforge.org`
[6] `http://lpsc.in2p3.fr/usine/`
[7] F. C. Jones, A. Lukasiak, V. Ptuskin, and W. Webber, Ap.J. **547**, 264 (2001).
[8] P. Blasi, E. Amato and P. D. Serpico, Phys. Rev. Lett. **109**, 061101 (2012) [arXiv:1207.3706 [astro-ph.HE]].
[9] P.A.M. Dirac, Proc. Camb. Phil. Soc. **26**, 361 (1930)
[10] R. Schlickeiser, Berlin, Germany: Springer (2002) 519 p
[11] C. Evoli, D. Gaggero, D. Grasso, and L. Maccione, JCAP **0810**, 018 (2008), `arXiv:0807.4730`

[12] G. Di Bernardo, C. Evoli, D. Gaggero, D. Grasso, and L. Maccione, JCAP **1303**, 036 (2013) `arXiv:1210.4546`
[13] L. Stawarz, V. Petrosian, and R.D. Blandford, Ap.J. **710** Issue 1, 236-247 (2010), `arXiv:0908.1094`
[14] M. Aguilar *et al.* [AMS Collaboration], Phys. Rev. Lett. **110**, no. 14, 141102 (2013).
[15] A. Mastichiadis, A.P. Marscher, and K. Brecher, Ap.J. **300**, 178-189 (1986)
[16] C.D. Dermer and R. Schlickeiser, A&A **252**, 414-420 (1991)
[17] V. Anguelov, S. Petrov, L. Gurdev, and J. Kourtev, J.Phys. G **25** 1733 (1999)