SF2A 2010
S. Boissier, M. Heydari-Malayeri, R. Samadi and D. Valls-Gabaud (eds)

HAVE WE SEEN DARK MATTER ANNIHILATION IN THE COSMIC-RAY ELECTRON AND POSITRON SPECTRA

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Abstract. Measurements of a rise in the cosmic positron fraction up to ~ 100 GeV by the PAMELA satellite have triggered putative interpretation attempts in terms of dark matter (DM) annihilation or decay, even though generic DM particle models are not expected to contribute to this signal. Here, we review the tricks that have been invoked to make DM-induced signals fit the data. We also recall how considering conventional astrophysical sources — supernova remnants (SNRs) and pulsars — in a consistent cosmic-ray (CR) propagation framework can easily explain these observations, despite large theoretical uncertainties. Although this does not dismiss potential DM contributions, this unfortunately makes the related background far too difficult to control for discovery purposes. Though the positron puzzle appears qualitatively solved in terms of standard astrophysics, substantial improvements in the CR source and propagation modelings are now clearly necessary to improve our understanding of the Galactic CR lepton budget and associated multi-wavelength diffuse emissions.

Keywords: dark matter, cosmic-ray propagation, cosmic-ray sources, pulsars, supernova remnants

1 Introduction

Indications of an increase in the CR positron fraction above a few GeV have been collected for quite a long time (Fanselow et al. 1969; Golden et al. 1987; Barwick et al. 1997; Alcaraz et al. 2000), but the recent PAMELA measurements have reached an unprecedented statistics allowing much more detailed analyses (Adriani et al. 2009). It turns out that this increase can hardly be explained in terms of secondary positrons* (Moskalenko & Strong 1998; Delahaye et al. 2009), though peculiar spatial effects are still worth being investigated into more details (Shaviv et al. 2009) — see also the original proposal by Roberts (2010) about a possible solar magnetic lens effects.

Antimatter CR excess signals as potential probes of DM annihilation were first proposed by Silk & Srednicki (1984) after one became aware of the power of gamma-ray and CR observations to constrain the DM properties (*e.g.* Gunn et al. 1978; Stecker 1978; Zeldovich et al. 1980). Later, as already mentioned by Tylka (1989), Baltz & Edsjö (1998) showed in detail that annihilation of supersymmetric neutralinos, one of the most popular DM candidate so far, could hardly generate observable features in the local positron spectrum unless the annihilation rate is substantially boosted, suggesting that DM substructures could play this amplifier role, following the idea of Silk & Stebbins (1993). It was recently shown that such subhalos can actually hardly be at the origin of the large required enhancement (Lavalle et al. 2007, 2008b), and that even an isolated such dark source, as proposed in Cumberbatch & Silk (2007), would lead to tensions with current gamma-ray constraints (Bringmann et al. 2009). Despite this apparent failure of dark matter particle models to naturally yield CR positrons in sufficient amount, an impressive number of papers has been released in the past few years to try to explain the PAMELA data in terms of DM annihilation or decay. We will discuss a few aspects of the available proposals below, but it is already worth noticing that all these works assumed the absence of astrophysical sources of positrons but secondaries when fitting the data.

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*For the non-expert reader, a primary cosmic ray is produced — or/and accelerated — at sources, whereas a secondary cosmic ray originates from nuclear interactions between primary CR nuclei and the interstellar gas (ISG).

Although interpretations in terms of standard astrophysical sources were only a few in the past decades (*e.g.* Arons 1981; Harding & Ramaty 1987; Boulares 1989; Aharonian et al. 1995; Chi et al. 1996), they all relied on quite sound physical arguments: pulsars were already predicted to produce a significant amount of electron-positron pairs only few years after their discovery (*e.g.* Sturrock 1970), which is now indirectly proven from the more recent observations of gamma-rays originating from pulsar magnetospheres. Another way to generate primary-like positrons, also relying on standard astrophysics and recently widely surveyed, is to invoke the diffusive acceleration of those secondary positrons created at SNR shocks (*e.g.* Berezhko et al. 2003; Blasi 2009). Nevertheless, we will focus here on the pulsar solution when discussing standard astrophysical explanations of the positron excess.

The outline of this proceeding is the following. We first recall the bases of electron-positron propagation in the Galaxy. Then, we revisit the case for the DM interpretation of the cosmic positron excess, showing how contrived this attempt can be. Afterwards, we discuss the requirements a model of astrophysical CR electrons and positrons should obey. We emphasize that including pulsars as positron sources can naturally lead to a good fit of the PAMELA data, with quite reasonable parameters. Finally, we conclude and discuss a few perspectives.

2 Electron and positron propagation in the galaxy

Reviews and books on CR propagation are numerous, and we refer the reader to *e.g.* Strong et al. (2007) for a recent review, and to Berezinskii et al. (1990) and Longair (1992, 1994) for valuable books. A detailed description of CR electron†propagation can be found in Delahaye et al. (2010).

Once produced, stable charged CRs (among which electrons) in the GeV-TeV energy range may experience different processes. The dominant ones are diffusion in space (due to scattering with magnetic turbulences and to convective winds) and diffusion in momentum (energy losses — negligible for CR nuclei — and diffusive reacceleration — negligible above a few GeV). Electron propagation in this energy range is almost completely set by spatial diffusion and energy losses, the latter being due to inverse Compton interactions with the interstellar radiation field (ISRF, including the CMB) and the Galactic magnetic field (synchrotron). In steady state and when convection is neglected, the master propagation equation associated with an electron density $\mathcal{N} \equiv dn/dE$ reads $-\vec{\nabla}\left\{K(E,\vec{x})\,\vec{\nabla}\mathcal{N}(E,\vec{x})\right\} - \partial_E\left\{b(E)\,\mathcal{N}(E,\vec{x})\right\} = \mathcal{Q}(E,\vec{x})$, where $\mathcal{Q}$ is the source term, $K(E,\vec{x})$ is the diffusion coefficient, and $b(E) = -dE/dt$ is the energy loss rate; being set by Compton interactions,the latter strongly increases with energy ($b(E) \propto E^2$ in the Thomson approximation). The typical energy loss timescale is $\tau_l \approx 10^{16}$s at 1 GeV for Galactic electrons. Note that the diffusion coefficient can, in most of relevant situations, be considered as homogeneous, and is usually modeled as a power law, $K(E) \simeq K_0(E/E_0)^\delta$. The normalization and index can be determined from observed secondary-to-primary ratios of nuclei species which mostly depend on K_0/L, where L is the half-thickness of the diffusion zone (see *e.g.* Maurin et al. 2001; Putze et al. 2010) — values are usually found close to $K_0(E_0 = 1\,\mathrm{GeV}) \approx 3.4\times10^{27}\mathrm{cm}^2/\mathrm{s}$, $\delta \approx 0.7$ and $L \approx 4$ kpc. The above equation (without spatial boundaries) admits a solution in the form of a Green function $\mathcal{G}(E,\vec{x}\leftarrow E_s,\vec{x}_s) = \frac{\exp\left\{-\frac{(\vec{x}_s-\vec{x})^2}{\lambda^2}\right\}}{b(E)(\pi\,\lambda^2)^{\frac{3}{2}}}$ with $\lambda^2 \equiv 4\int_E^{E_s} dE'\,\frac{K(E')}{b(E')}$, where λ is mean propagation scale, of the order of $\sqrt{K_0\,\tau_l} \approx 2$ kpc, *i.e.* usually less than L (spatial boundaries can therefore be neglected to a good approximation): due to the very efficient energy losses, electrons with energies above a few tens of GeV are mostly local. This Green function allows the computation of the electron density at the Earth given a source term $\mathcal{Q}(E_s,\vec{x}_s)$ which features the spatial and energy distributions before propagation.

Primary and secondary CRs of astrophysical origin are injected in the Galactic plane, where the standard sources (SNRs and pulsars) and the ISG are located. For secondary positrons, which will constitute the "background" in the next sections of this proceeding, one can approximate the source term as a power law spectrum of index γ_s, reminiscent from the CR nuclei index, and flatly distributed in the Galactic plane, so that $\mathcal{Q}_s \propto E^{-\gamma_s}\delta(z)$. Thus (in the Thomson approximation for the energy losses), the secondary positron flux can be derived analytically: $\phi_s \propto \sqrt{\tau_l/K_0}\,E^{-\tilde{\gamma}_s}$, where $\tilde{\gamma}_s = \gamma_s + 0.5(\alpha+\delta-1)$ — $\alpha \equiv \ln(b(E)/b(E_0)/\ln(E/E_0)$, *i.e.* $\alpha = 2$ in the Thomson approximation. Note that this reasoning also holds for primaries when neglecting local discrete sources. By using the index inferred from considering CR nuclei interactions with the ISG, *i.e.* $\gamma_s \simeq 2.75$, one readily gets $\tilde{\gamma}_s \simeq 3.45$, quite close to the observed positron-only index (Delahaye et al. 2009, 2010). Nevertheless, predictions for the secondary positron flux fail to fit the positron fraction data — $f_{e^+} \equiv \phi_{e^+}/(\phi_{e^-}+\phi_{e^+})$ — leading instead to a fraction decreasing with energy (Delahaye et al. 2009, 2010). Nevertheless, taking into account the hardening in the proton spectrum above ~ 2 TeV recently observed by the CREAM experiment (Ahn et al. 2010) should result into a slightly harder secondary positron spectrum. This effect remains to be checked in detail though we do not expect it to amplify the secondary flux by more than 50%, while an enhancement factor $\gtrsim 5$ around 100 GeV is necessary to fit the data.

3 Dark matter interpretation of the positron excess

DM particle scenarios rely on physics beyond the standard model. In most of them, *e.g.* in the so-called weakly interacting massive particle (WIMP) paradigm, the total DM abundance is set by annihilation in the early universe (for reviews, see *e.g.* Jungman et al. 1996; Bergström 2000; Murayama 2007). Originally in thermal and chemical equilibrium with the primordial plasma after inflation, DM chemically decouples when the annihilation rate becomes smaller than the expansion rate of the universe. This usually has to happen before big bang nucleosynthesis (BBN), which must not be unsettled, when WIMPs are already non-relativistic — referred to as cold DM (CDM). Therefore, cosmology imposes strong constraints to the annihilation cross section, provided the expansion rate of the universe before BBN is taken standard[‡]. Typically, to get a relic abundance of $\Omega_{\rm DM} \approx 0.1/h^2$, WIMPs need a thermally averaged annihilation cross section of $\langle \sigma v \rangle \approx 3 \times 10^{-26}{\rm cm}^3/{\rm s}$.

Annihilation is revived after DM has collapsed to form galaxies, its density being large enough in these objects. WIMPs annihilation now occurs almost at rest and proceeds into pairs of standard model particles, some of them further hadronizing or decaying, usually leading to the injection of CRs with continuous energy spectra. Attempts to detect these annihilation products refer to as *indirect detection* (see *e.g.* Salati 2007). The knowledge of the DM density distribution is crucial to compute the induced CR fluxes, since the annihilation rate scales like the squared density; it is generally expressed in terms of the ratio of the mass density profile ρ to the particle mass m_χ, $n_\chi = \rho/m_\chi$, and constrained theoretically from N-body simulations and observationally from kinematic data (*e.g.* Klypin et al. 2002).

In the case of high energy positrons, which are short range CRs, the most relevant input is the local DM density set by $\rho_\odot \approx 0.3\,{\rm GeV/cm^3}$. At sufficiently high energy, positrons lose their energy before they substantially diffuse, so that one can neglect spatial diffusion to a good approximation, provided the injection rate does not fluctuate too much over short distances. In that case, the Green function defined earlier becomes $\mathcal{G}(E, \vec{x} \leftarrow E_s, \vec{x}_s) \overset{\lambda \to 0}{\approx} \delta^3(\vec{x}_s - \vec{x})/b(E)$. The positron flux at the Earth generated by DM annihilation is thus completely analytical: $\phi_{e^+}(E) \approx \frac{\beta\, c}{4\pi} \frac{\langle \sigma v \rangle}{2\, b(E)} \left[\frac{\rho_\odot}{m_\chi}\right]^2 \int_E^{m_\chi} dE_s\, \frac{dN_{e^+}}{dE_s}$ leading to:

$$\phi_{e^+}(E) \approx \phi_\chi^0 \left[\frac{\langle \sigma v \rangle}{3 \times 10^{-26}{\rm cm}^3/{\rm s}}\right] \left[\frac{\tau_l}{10^{16}{\rm s}}\right] \left[\frac{\rho_\odot/(0.3\,{\rm GeV/cm^3})}{(E/1\,{\rm GeV})(m_\chi/100\,{\rm GeV})}\right]^2 \int_E^{m_\chi} dE_s\, \frac{dN_{e^+}}{dE_s}\ , \qquad (3.1)$$

where we find $\phi_\chi^0 = 3.2 \times 10^{-6}$ ${\rm cm^{-2}\ s^{-1}\ GeV^{-1}\ sr^{-1}}$ — if WIMPs are Dirac fermions, an additional factor of 1/2 must be accounted for. Notice the dependence on energy and WIMP mass, which is explicit in this equation. We can further simplify it by assuming annihilation into electron-positron pairs, so that the injected spectrum $dN_{e^+}/dE_s = \delta(E_s - m_\chi)$. In this case, the positron flux associated with a WIMP mass of $m_\chi = 100$ GeV at an energy of 100 GeV is $\phi_\chi(E = m_\chi = 100\,{\rm GeV}) \approx 3.2 \times 10^{-10}{\rm cm^{-2}\ s^{-1}\ GeV^{-1}\ sr^{-1}}$, amazingly close to the value predicted for the secondary background at this energy. This means that such a model, provided a small amplification (or *boost*) by a factor of a few, could very well explain the observed rise in the positron fraction (Pieri et al. 2009). Nevertheless, such an exclusive annihilation into lepton pairs is quite a contrived situation for WIMPs with masses greater than a few GeV, which can neither rely on sound particle physics motivations nor be easily cooked up. For other annihilation final states, like heavy quarks or massive gauge bosons, the required boost factor is much larger (see left panel of Fig. 2 in Lavalle 2010). Since the annihilation cross section is fixed by the relic abundance, this low positron flux is a quite generic prediction, valid for most of motivated DM particle scenarios like in supersymmetry or extra-dimensions (Lavalle et al. 2008a).

At this stage, the question is: are there ways to amplify the predicted signal which would be motivated by some physical arguments? Actually, there are three different tracks one can explore: (i) enhancing annihilation cross section; (ii) playing with CR propagation: theoretical uncertainties allow some freedom; (iii) considering extra (local) sources of DM.

[†] The term *electrons* will characterize both electrons and positrons when discussing general propagation features.

[‡] This could change *e.g.* in the context of quintessence as a solution to dark energy (*e.g.* Salati 2003).

3.1 Enhanced annihilation cross section

The physical motivation behind this possibility is that when WIMPs are much more massive than an exchanged virtual boson field during the annihilation process, then a resonance can occur, which can strongly amplify the cross section (referred to as *Sommerfeld enhancement*). This effect usually scales like the inverse squared velocity of WIMPs, so it is stronger in galaxies today than at the decoupling time in the early universe. Nevertheless, this effect concerns a very small part of the WIMP parameter space, and suffers severe constraints: all signals associated with the amplified final state are enhanced the same, which generally leads the predicted antiproton flux to overshoot the observational bounds, unless heavy DM particles annihilate only into leptons, which is quite contrived (Cirelli et al. 2009). Such a possibility has therefore poor relevance.

3.2 Impact of theoretical uncertainties in CR propagation

Since DM-induced CRs are produced everywhere in the Galaxy, enlarging the diffusion zone in the range permitted by theoretical uncertainties may increase the flux predictions. Nevertheless, for positrons, this would only affect the low energy part of the spectrum, since high energy positrons, bound to be short range by efficient energy losses, must originate from very local regions. Therefore, tuning the propagation parameters also fails to enhance the high energy positron flux (Lavalle et al. 2008b; Delahaye et al. 2008) — the energy loss parameters being quite well constrained.

3.3 Considering extra DM sources

The impact of DM substructures wandering in the Galactic halo was first emphasized by Silk & Stebbins (1993). Nevertheless, predicting the positron boost factor associated with these subhalos is not trivial, since it depends on both their inner properties and their spatial distribution (Lavalle et al. 2007). Even when spanning the full ranges for prescriptions coming from cosmological structure formation theory, it was actually shown that these Galactic subhalos could not increase the signal by a large factor, with an upper limit $\lesssim 20$ (Lavalle et al. 2008b). However, this upper bound is associated with a large statistical variance at high energy reflecting the fact that though the probability of finding a massive enough subhalo close to the Earth is vanishingly small, this would amplify the signal by a larger factor if this occurred. Nevertheless, even this tricky situation suffers strong constraints coming *e.g.* from gamma-ray observations which strongly disfavors it as an explanation of a rising positron fraction (Bringmann et al. 2009).

To conclude this section, we emphasize that the DM solution to the cosmic positron issue is by itself very contrived and lacks strong physical motivations. Likewise, most of attempts are now excluded by complementary constraints coming from other cosmic messengers.

4 Towards a consistent model of CR leptons

We have already underlined that pulsars have long been proposed as sources of CR positrons, and were even demonstrated, more than 15 years ago, to provide a good fit to the observed positron fraction above 5 GeV. Since there are also other astrophysical proposals beside pulsars that could provide additional positrons, the question is not really whether standard astrophysics can explain the data, but what a consistent CR model should look like — note that the whole set of data such a model has to fit must also include the individual spectra of electrons and positrons, and their sum as recently measured by Fermi and HESS up to TeV energies (Abdo et al. 2009; Aharonian et al. 2008). In fact, it is probably because it was wrongly believed that a *standard model* of CRs existed that PAMELA measurements triggered such a “buzz”. Indeed, the most advertized CR model called `GALPROP` (Strong & Moskalenko 1998; Moskalenko & Strong 1998), which was too naively taken as a reference in the debate on positrons, (i) was not including any source of primary positrons at that time and (ii) was treating the injection of electrons with a smooth and continuous spatial distribution of SNRs associated with an empirical energy spectrum, which also led to the claim of an excess in the Fermi data. Aside from the lack of primary positrons in this model, it has been known for a long time that considering a smooth spatial distribution of sources for high energy electrons failed for local predictions, just because the discreteness of local sources has to manifest itself at high energy in the form of spectral fluctuations in the data (Shen 1970; Kobayashi et al. 2004). Yet, this confusion cannot be attributed to the `GALPROP` model itself, since one of its main goals was to investigate the diffuse Galactic multi-wavelength emissions originating from CR interactions with the interstellar medium (ISM), either hadronic and electromagnetic, rather than the local electron budget.

Therefore, while we can fairly talk about a *standard paradigm* for CR propagation and sources, a *standard model* is still far from achieved. A consistent prediction of the CR electron and positron fluxes at the Earth (or at any point in the Galaxy) should at least include the contributions of (i) secondaries, (ii) a smooth distribution of sources for the distant (and therefore low energy) primary component, with a radial cut-off set to a distance from the Earth for which the source discreteness effects can safely be averaged out (∼ 2 kpc), and (iii) the discrete sources located inside this cut-off radius. For the latter contribution, different catalogs are available for pulsars and SNRs to constrain the relevant parameters, *e.g.* the position and age estimates (*e.g.* Manchester et al. 2005; Green 2009).

We have mostly discussed the spatial distribution that a consistent CR electron model. Nevertheless, there is still a major issue to mention: the injection from SNRs and pulsars. Indeed, though we can reasonably motivate an average power law spectrum associated with an injection rate set by the explosion rate of supernovæ and some energetics considerations for the distant component (*e.g.* Malkov & O'C Drury 2001), an accurate modeling of local sources is of paramount importance, since few of them might dominate the overall spectrum above ∼ 100 GeV. Thus, the overall spectrum piles up all individual contributions and likely departs from a simple power law. The individual amplitudes and spectral shapes strongly depend not only on the injected spectra, but also on the source distances and ages (Delahaye et al. 2010). Moreover, the dynamics of CR (both nuclei and electrons) injection into the ISM is still unclear (see discussion in *e.g.* O'C. Drury 2010; Blasi & Amato 2010). Nevertheless, the big advantage of local sources is that we have at hand a numerous multi-wavelength observations to build a rather constrained model for each of them (see an example in Tatischeff 2009). Such a thorough study involving sophisticated modelings for both local pulsars and SNRs remains to be achieved, though some preliminary efforts have already been undergone in this direction. Delahaye et al. (2010) have notably demonstrated that considering the observational properties of local sources is sufficient to explain the whole set of data on CR electrons and positrons despite the large theoretical uncertainties, without overtuning the parameters. This paves the road for further developments.

5 Conclusion

We have discussed the DM interpretation of the so-called electron and positron excesses, showing that it was likely too contrived to be supported from reasonable grounds, though one cannot formally exclude a DM contribution to the electron and positron spectra. We have also emphasized that consistently considering well known positron sources like pulsars can easily explain the current available data, despite the still large theoretical errors associated with the predictions. This not only means that the explanation to these excesses is no longer an issue, but also, unfortunately, that the positron channel is no longer an interesting discovery channel in frame of indirect DM detection. Indeed, the uncertainties affecting the predictions make the background to DM searches very hard to control.

Nevertheless, these new measurements of high energy CR electrons allow us to refine the current models of CR propagation and sources. Beside studying more sophisticated propagation treatments (*e.g.* Shalchi 2009), improving and testing the physics of CR injection from sources is likely an important topic for the next few years, which can now be implemented thanks to these unprecedented new data. Finally, clarifying our understanding of local CR electrons will have a paramount impact on the predictions for associated multi-wavelength electromagnetic diffuse emissions on the Galactic scale. Among interesting topics, this may provide novel approaches to study the Galactic magnetic fields through the synchrotron emission, and also the diffuse gamma-ray emission from the Galactic center. It is clear that the forthcoming lower frequency data expected from instruments like Planck or Herschel (Tauber et al. 2010; Walmsley et al. 2010) will be precious in this research field, as well as higher energy data on local electrons expected from AMS-02[§].

I am grateful to the PCHE scientific committee for having selected this topic among so many other interesting ones for the plenary PCHE talk. It is also a pleasure to thank some of my collaborators in this field for participation to the work itself and/or interesting discussions, namely T. Delahaye, R. Lineros, A. Marcowith, D. Maurin and P. Salati.

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