Dark matter signals in space

Pierre Salati
LAPTH, Université de Savoie, CNRS, B.P.110, F-74941 Annecy-le-Vieux Cedex, France
E-mail: salati@lapp.in2p3.fr

Abstract. The confirmation by the PAMELA collaboration of a positron excess above 10 GeV has triggered a lot of excitement in the field of particle astrophysics. This excess could be the first long waited hint of the presence of massive and weakly interacting species in the halo of the Milky Way. If so, the nature of the astronomical dark matter is about to be unveiled after more than seventy years of unsuccessful searches. This review summarizes the state of the art, a year of bubbling activity after the PAMELA announcement. The dark matter candidates which can potentially lead to a positron excess have quite special properties. They are severely constrained by radio and gamma observations unless they are tightly packed inside improbable or bizarre dark matter clumps. These species could also be unstable with abnormally long lifetimes. Although the positron excess could be generated by annihilating and/or decaying dark matter particles, William of Ockham would warn us that a more natural explanation is to be found in pulsars for instance, and that entia non sunt multiplicanda praeter necessitatem.

1. Evidence for primary cosmic ray positrons
The ATIC [1], HESS [2, 3] and Fermi [4] collaborations have recently reported measurements of the total cosmic ray (CR) electron and positron flux at high energy. The Fermi-LAT instrument in particular has collected high precision data between 20 GeV and 1 TeV which can be fitted by the simple power-law spectrum [5]

\[ \Phi_{e^\pm} = \left\{ 175.40 \pm 6.09 \text{ GeV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \right\} \epsilon^{-\left(3.045\pm0.008\right)}, \] (1)

where \( \epsilon \) denotes the electron or positron energy expressed in units of GeV. Primary CR electrons are believed to originate from the interstellar medium – like most of the primary CR nuclei – and are accelerated by supernovae driven shock waves which inject them with a spectral index \( \alpha \sim 2.2 \pm 0.1 \) inside the Milky Way disc. They subsequently diffuse on the inhomogeneities of the galactic magnetic field with an effective space diffusion coefficient \( K \) proportional to \( \epsilon^\delta \). In the GeV-TeV regime, CR electrons lose energy through synchrotron radiation as they spiral in the magnetic fields and by inverse Compton scattering (ICS) on the CMB and on galactic stellar light. A detailed investigation [6] leads to a CR electron flux at the earth of the form

\[ \Phi_{e^-} \propto \epsilon^{-\alpha - 0.5 - \delta/2}, \] (2)

with a spectral index of order 3.05 \pm 0.15, in reasonable agreement with the Fermi-LAT measurement. The value of \( \delta = 0.7 \) used here may seem too large to some colleagues [7]. It suffices then to increase \( \alpha \) in order to match the Fermi-LAT spectrum. The latter also contains a small admixture of secondary electrons and positrons which are produced by CR
primary protons and helium nuclei impinging on the interstellar gas. These spallation reactions generate many charged pions which eventually decay into positrons and in a lesser extent into electrons. The source spectral index is set by the CR proton and helium nuclei fluxes. With a value $\alpha = 2.7$, we expect a spectral index of $3.55 \pm 0.05$ for that secondary component which is nonetheless swamped in the total flux.

The PAMELA collaboration has measured [8] the positron fraction $e^+ / e^- + e^+$ on a large energy range. From the above mentioned arguments, we would naively expect that fraction to decrease with energy as $\epsilon^{-1/2}$. A more refined analysis [6] confirms that a CR electron spectral index as hard as 3.045 is associated to a decrease of the positron fraction above 10 GeV. The PAMELA measurements establish on the contrary that the positron fraction increases at high energy. This very important observation is in contradiction with a pure secondary origin for the positrons. Primary sources which directly inject these particles in the interstellar medium are necessary.

2. DM species with quite special properties

The positron excess, clearly established by the PAMELA collaboration [8] a year ago, has triggered since then an intense activity in our field. The excess may be related to the astronomical dark matter (DM), an essential component of the universe known to be non baryonic and the nature of which is still unresolved. DM could be made of weakly interacting massive particles (WIMPs) yet to be discovered at accelerators. According to what is now a well accepted working hypothesis, the DM species pervade the galactic halo where they mutually annihilate into a host of lighter particles, including positrons and antiprotons. WIMP annihilations are a source of primary positrons [9] with a production rate given by

$$q_{e^+} = \frac{1}{2} \langle \sigma_{\text{ann}} v \rangle \left( \frac{\rho_\chi}{m_\chi} \right)^2 f(\epsilon).$$  (3)

If the WIMPs are thermally produced during the big bang, their relic abundance matches the WMAP value [10] of $\Omega_\chi h^2 = 0.1131 \pm 0.0034$ provided that their annihilation cross section at the time of decoupling is equal to $\langle \sigma_{\text{ann}} v \rangle \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. The energy distribution $f(\epsilon)$ of the positrons produced in a single annihilation is set by the WIMP type. High energy positrons (and electrons) cannot diffuse on long distances and those detected at the earth must have been produced locally, hence a value of $\rho_\odot = 0.3 \text{ GeV cm}^{-3}$ for the WIMP density $\rho_\chi$. Baring in mind these bench mark values, one may estimate $q_{e^+}$ and eventually the DM positron flux $\Phi_{e^+}$. Alas, the values derived for a large choice of DM candidates and for various DM galactic distributions are way too small to account for the observed excess. For a WIMP mass $m_\chi$ of 1 TeV, the DM positron production rate $q_{e^+}$ needs to be enhanced by a factor of $\sim 10^3$ in order to match the PAMELA measurements, as shown in the left panel of figure 1.

To save the WIMP explanation of the PAMELA positron anomaly, a first remedy is the possibility that $\langle \sigma_{\text{ann}} v \rangle$ is much larger than what is currently assumed. Three directions at least have been explored so far. To commence, WIMP decoupling in the early universe takes place conventionally during a period of radiation domination. If the universe at that time is dominated by another component, like a scalar field rolling down its potential [11, 12], the expansion rate is significantly increased and the same WIMP relic abundance $\Omega_\chi$ requires now a much larger annihilation cross section. Another possibility is that WIMPs do not decouple from the primordial plasma. In this class of less natural scenarios, a non-thermal production takes place through the decay of heavier species like gravitinos or moduli fields [13]. The WIMP relic abundance $\Omega_\chi$ is no longer determined by $\langle \sigma_{\text{ann}} v \rangle$. It depends on the production rate and lifetime of these unstable heavier states. A final solution relies on the so-called Sommerfeld effect [14]. If the DM species are massive enough and interact through the exchange of a light particle $\phi$, they
are attracted towards each other at sufficiently low velocities. Their wave function is focalized at the interaction point and the annihilation cross section can be significantly enhanced. Scenarios based on that effect have been recently proposed [15–17], reviving the idea of secluded dark matter [18]. WIMPs are still thermally produced in the early universe. Their annihilation cross section at that time is equal to the conventional value of $3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$. As the universe expands, the average WIMP velocity $\beta$ decreases. The Sommerfeld effect sets in as soon as the WIMP kinetic energy is dominated by the interaction energy, i.e., when $\beta$ no longer exceeds the effective WIMP coupling constant $\alpha'$. The cross section increases and may be today large enough to account for the PAMELA positron excess. The enhancement saturates when the WIMP de Broglie wavelength $\sim 1/m_\chi \beta$ exceeds the range $\sim 1/m_\phi$ of the interaction. This occurs for $\beta \leq m_\phi/m_\chi$. The annihilation cross section is resonantly increased whenever $\alpha' m_\phi \sim \alpha'^2 m_\chi/n^2$ where $n$ is an integer [19].

Figure 1. The pedagogical case of a 1 TeV LSP annihilating into a $W^+ W^-$ pair is presented. In the left panel, the positron signal which this DM species yields has been increased by a factor of 400, hence the solid curve and a marginal agreement with the PAMELA data. Positron fraction data are from HEAT [20], AMS-01 [21, 22] and PAMELA [8]. If the so-called Sommerfeld effect [14] is invoked to explain such a large enhancement of the annihilation cross section, the same boost applies to antiprotons and leads to an unacceptable distortion of their spectrum as indicated by the red solid line of the right panel. Figures and caption are borrowed from [23].

Irrespective of the mechanism enhancing $\langle \sigma \text{ann} v \rangle$, WIMPs should not overproduce antiprotons [23, 24]. The annihilation channels through which these antimatter species are produced must be significantly suppressed. The antiproton to proton ratio measured by the PAMELA collaboration [25] does not show actually any excess and is consistent with a pure secondary origin as featured in the right panel of figure 1. Therefore, on top of an abnormally large annihilation cross section, WIMPs preferentially annihilate into charged leptons, a feature which is unusual in supersymmetry but more typical of Kaluza-Klein theories. From a phenomenological point of view, WIMP annihilations must proceed either directly to lepton pairs or, in some models, through the production of the above mentioned light mediator species $\phi$ which subsequently decay into leptons via

$$\chi + \chi \rightarrow \phi + \phi \rightarrow l^+ l^- l^+ l^-.$$ (4)
The possibility to explain the PAMELA positron excess by leptophilic DM particles with enhanced annihilation cross section has been extensively studied over the past year. Depending on its magnitude, the injection of high energy positrons and electrons is associated to clear astrophysical signatures [26]. As they spiral along the galactic magnetic field lines, these particles produce a radio emission through synchrotron radiation. They also inverse Compton scatter photons from the CMB and stellar light. Finally, the charged leptons released by the WIMP annihilations can radiate high energy gamma rays. After an extensive scan [27–29] of the various possibilities, the region of the \((m_\chi, \langle \sigma v \rangle)\) plane compatible with the PAMELA and Fermi-LAT measurements is found to be excluded for most of the leptophilic DM candidates. The most stringent limit arises from the synchrotron radio emission produced at the galactic center, a region where the DM distribution may be cuspy and where magnetic fields should be strong. That limit weakens considerably though as soon as a cored isothermal DM distribution is preferred to the usual Einasto or NFW profile. In that case, leptophilic WIMPs are not excluded and could be a viable explanation of the positron anomaly. A more reliable tool is provided by the ICS of the positrons and electrons produced by WIMP annihilation at high galactic latitude, a region which is less subject to uncertainties than the center of the Milky Way. A careful investigation [30], performed only in the case where the WIMPs annihilate directly into lepton pairs, excludes values of \(m_\chi\) larger than 1 TeV. Another model independent analysis implies the injection in the intergalactic medium at redshift \(\sim 1000\) of the secondary particles produced by WIMP annihilation. The recombination process is affected and an imprint is left on the CMB, which may be searched for in the high precision WMAP data [31]. Most of the PAMELA compatible leptophilic DM candidates still survive that test [32] but will be probed by the Planck mission.

3. The effect of clumpiness on DM annihilation

Another way to increase the positron production rate (3) relies on the existence of clumps inside the smooth DM galactic distribution. Because \(\langle \rho_\chi^2 \rangle\) is always larger than \(\langle \rho_\chi \rangle^2\), inhomogeneities tend to enhance \(q_{e^\pm}\), a quantity proportional to the square of the DM density. How large is that enhancement depends on the position of the substructures with respect to the DM smooth component of the Milky Way. The inner structure of clumps as well as their mass distribution are also key factors. The lower mass cut-off and the concentration-to-mass relation of the DM substructures come finally into play. A statistical analysis is mandatory since we live inside one particular realization of the clump distribution to be taken out of an infinite set of similar realizations. Using the tools specifically forged for computing the odds of that galactic lottery [33], a comprehensive analysis [34] indicates that the boost factor to be applied to \(q_{e^\pm}\) in the case of a \(\Lambda\)CDM universe cannot exceed at most a factor of 20 at high energy. The correct value is presumably much smaller, i.e. of order unity [35].

Although a clumpy DM halo does not lead on average to an increase of the positron flux at the earth, the statistical variance of the boost factor is large at high energy, hence the existence of configurations where \(q_{e^\pm}\) could be significantly enhanced. The possibility that a DM clump lies for instance in the vicinity of the solar system has been suggested [36, 37] as an explanation for the PAMELA positron anomaly. Such a local substructure would actually outshine the rest of the galactic DM distribution. Alas, the probability that such a situation occurs in the DM halo of the Milky Way is vanishingly small as demonstrated in a recent analysis [38] based on the results of the cosmological N-body simulation Via Lactea II [39]. In the favorable case of a 100 GeV DM species annihilating into \(e^\pm\) pairs, the PAMELA positron excess is best fitted by a subhalo with annihilation volume

\[
\xi = \int_{\text{clump}} \left\{ \rho_{e}(x)/\rho_{\odot} \right\}^2 d^3x \sim 114 \text{ kpc}^3 ,
\]
located at 1.22 kpc from the earth. That configuration has a probability of only 0.37 percent to occur. Other arrangements are even less probable.

According to scenario B of [40], when a DM halo with mass $10^7 M_\odot$ forms at redshift $\sim 20$, a fraction of $\sim 3$ percent of the gas which it contains cools and collapses as a pressure supported disc. A baryonic mass of $10^5 M_\odot$ looses its angular momentum and is transferred at the center of that disc where it forms an intermediate mass black hole (IMBH). During the process, DM is dragged inwards and is adiabatically compressed onto the central object around which a large density enhancement dubbed minispike develops. Although minispikes have an outer radius of only 3 pc on average, their inner DM density reaches the annihilation limit close to the IMBH, hence typical annihilation volumes $\xi$ as large as $3.3 \times 10^6$ kpc$^3$ for a 1 TeV WIMP with thermal annihilation cross section. A hundred minispikes are expected today in the halo of the Milky Way. The probability that one of these objects lies close enough to the earth to generate a positron excess matching the PAMELA measurements reaches 84 percent [41] for the above mentioned DM species and a pure $e^\pm$ annihilation channel.

4. Decaying dark matter

Finally, the possibility of unstable DM candidates with very large lifetimes has also been explored [42, 43]. Irrespective of their production mechanism in the early universe, unstable species could in principle generate the PAMELA signal. The production rate (3) may be written now as

$$q_{e^+} = \tau^{-1}_{\text{dec}} \left\{ \frac{\rho_\chi}{m_\chi} \right\} f(\epsilon),$$

(6)

where the quantity $1/2 \times \langle \sigma_{\text{ann}} v \rangle \times \{\rho_\chi/m_\chi\}$ has been replaced by the decay rate $\tau^{-1}_{\text{dec}}$. For a 1 TeV WIMP, a lifetime of order $2 \times 10^{26}$ sec is required to reproduce the positron excess. The synchrotron radio emission from the galactic center is no longer a problem even in the case of a NFW or Einasto profile since the positron production rate from decaying DM is proportional to $\rho_\chi$ and not to $\rho_\chi^2$. The lifetime needs to be fine tuned though. Higher dimension operators must be invoked to explain the large value of $\tau_{\text{dec}}$ required by PAMELA. If a four-fermion point-like coupling is responsible for the WIMP instability, we anticipate [44] a decay rate $\propto m_\chi^5/M^4$ where $M$ denotes the typical scale of the underlying high energy theory. If factors of 2 and $\pi$ are neglected, a GUT mass $M \sim 2.3 \times 10^{16}$ GeV could lead to the required lifetime. Notice that the DM species must also be leptophilic otherwise antiprotons are also overproduced.

5. Ockham’s razor

Although the PAMELA excess can be explained by annihilating or decaying WIMPs, William of Ockham would refresh our enthusiasm by warning us that more natural explanations are provided by existing astrophysical objects. Pulsars for instance are highly magnetized neutron stars where strong electric fields can extract charged particles from the surface. Stripped electrons generate electromagnetic showers inside the magnetosphere and produce positrons which are eventually released in the interstellar medium [45]. An injection spectrum $\alpha = 1.5$ is necessary to match the PAMELA observations [46].

The possibility that CR spallations could take place during the acceleration process has also been proposed [47, 48]. As particles are accelerated by a supernova driven shock wave, they also interact with the material flowing through the shock and generate secondary species like positrons. The latter are then accelerated and replenish the high energy tail of the positron spectrum. According to that scenario, we should also expect an increase with energy of the B/C ratio as well as an antiproton excess above $\sim 100$ GeV [49].
Acknowledgments

Pierre Salati would like to thank the organizers for the inspiring and exciting atmosphere of this very nice meeting.

References

[1] Chang J et al. 2008 Nature 456 362–365
[2] Aharonian F et al. (H.E.S.S.) 2008 Phys. Rev. Lett. 101 261104 (Preprint 0811.3894)
[3] Aharonian H E S S C F 2009 (Preprint 0905.0105)
[4] Abdo A A et al. (The Fermi LAT) 2009 Phys. Rev. Lett. 102 181101 (Preprint 0905.0025)
[5] Grasso D et al. (FERMI-LAT) 2009 Astropart. Phys. 32 140–151 (Preprint 0905.0636)
[6] Delahaye T et al. 2009 Astron. Astrophys. 501 821–833 (Preprint 0809.5268)
[7] Strong A W, Moskalenko I V and Reimer O 2004 Astrophys. J. 613 962–976 (Preprint astro-ph/0406254)
[8] Adriani O et al. (PAMELA) 2009 Nature 458 607–609 (Preprint 0810.4995)
[9] Delahaye T, Lineros R, Donato F, Fornengo N and Salati P 2008 Phys. Rev. D77 063527 (Preprint 0712.2312)
[10] Hinshaw G et al. (WMAP) 2009 Astrophys. J. Suppl. 180 225–245 (Preprint 0803.0732)
[11] Salati P 2003 Phys. Lett. B571 121–131 (Preprint astro-ph/0207396)
[12] Profumo S and Ullio P 2003 JCAP 0311 006 (Preprint hep-ph/0309220)
[13] Kane G, Lu R and Watson S 2009 Phys. Rev. Lett. 102 071301 (Preprint 0810.0713)
[14] Diemand J et al. (HEAT) 2009 Phys. Rev. Lett. 102 051301 (Preprint 0809.5292)
[15] Cirelli M, Franceschini R and Strumia A 2008 Nucl. Phys. B800 204–220 (Preprint 0802.3378)
[16] Aharonian F, Papucci M, Strumia A and Volansky D 2009 JCAP 0903 009 (Preprint 0811.3744)
[17] Cirelli M, Kadastik M, Raidal M and Strumia A 2009 Nucl. Phys. B813 1–21 (Preprint 0809.2409)
[18] Adriani O et al. 2009 Phys. Rev. Lett. 102 051101 (Preprint 0810.4994)
[19] Caldwell R R and Dave R 2009 Phys. Rev. D79 023505 (Preprint 0811.3049)
[20] Bertone G, Cirelli M, Strumia A and Taoso M 2009 JCAP 0903 009 (Preprint 0811.3744)
[21] Bergstrom L, Bertone G, Bringmann T, Edsjo J and Taoso M 2009 Phys. Rev. D79 081303 (Preprint 0812.3895)
[22] Bertone G, Cirelli M, Strumia A and Taoso M 2009 JCAP 0903 009 (Preprint 0811.3744)
[23] Bergstrom L, Bertone G, Bringmann T, Edsjo J and Taoso M 2009 Phys. Rev. D79 081303 (Preprint 0812.3895)
[24] Cirelli M, Kadastik M, Raidal M and Strumia A 2009 Nucl. Phys. B813 1–21 (Preprint 0809.2409)
[25] Adriani O et al. 2009 Phys. Rev. Lett. 102 051101 (Preprint 0810.4994)
[26] Borriello E, Cuoco A and Miele G 2009 Astrophys. J. 699 L59–L63 (Preprint 0903.1852)
[27] Bertone G, Cirelli M, Strumia A and Taoso M 2009 JCAP 0903 009 (Preprint 0811.3744)
[28] Bergstrom L, Bertone G, Bringmann T, Edsjo J and Taoso M 2009 Phys. Rev. D79 081303 (Preprint 0812.3895)
[29] Cumberbatch D T and Silk J 2007 Mon. Not. Roy. Astron. Soc. 374 455–465 (Preprint astro-ph/0602320)
[30] Hooper D, Stubbins A and Zurek K M 2009 Phys. Rev. D79 103513 (Preprint 0812.3202)
[31] Galli S, Iocco F, Bertone G and Melchiorri A 2009 Phys. Rev. D80 023505 (Preprint 0905.0003)
[32] Salati P, Padmanabhan N and Finkbeiner D 2009 Phys. Rev. D80 043526 (Preprint 0906.1197)
[33] Hooper D, Profumo S and Salati P 2009 Phys. Rev. D80 035023 (Preprint 0904.0812)
[34] Diebold J et al. 2008 Nature 454 735–738 (Preprint 0805.1244)
[35] Bertone G, Zentner A R and Silk J 2005 Phys. Rev. D72 103517 (Preprint astro-ph/0509565)
[36] Bringmann T, Lalonde J and Salati P 2009 Phys. Rev. Lett. 103 161301 (Preprint 0902.3665)
[37] Ibarra A and Tran D 2009 JCAP 0902 021 (Preprint 0811.1555)
[38] Ibarra A, Tran and Weniger C 2009 (Preprint 0906.1571)
[39] Chen C R, Nojiri M M, Takahashi F and Yanagida T T 2009 Prog. Theor. Phys. 122 553–559 (Preprint 0811.3357)
[40] Profumo S 2008 (Preprint 0812.4457)
[41] Hooper D, Blasi P and Serpico P D 2009 JCAP 0901 025 (Preprint 0810.1527)
[42] Blasi P 2009 Phys. Rev. Lett. 103 051104 (Preprint 0903.2379)
[43] Ahlers M, Mertsch P and Sarkar S 2009 (Preprint 0909.4060)
[44] Blasi P and Serpico P D 2009 Phys. Rev. Lett. 103 081103 (Preprint 0904.0871)