Results from PAMELA, ATIC and FERMI: Pulsars or Dark Matter?

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(Dated: December 3, 2009)

It is well known that the dark matter dominates the dynamics of galaxies and clusters of galaxies. Its constituents remain a mystery despite an assiduous search for them over the past three decades. Recent results from the satellite-based PAMELA experiment detect an excess in the positron fraction at energies between $10 - 100$ GeV in the secondary cosmic ray spectrum. Other experiments namely ATIC, HESS and FERMI show an excess in the total electron ($e^+ + e^-$) spectrum for energies greater 100 GeV. These excesses in the positron fraction as well as the electron spectrum could arise in local astrophysical processes like pulsars, or can be attributed to the annihilation of the dark matter particles. The second possibility gives clues to the possible candidates for the dark matter in galaxies and other astrophysical systems. In this article, we give a report of these exciting developments.

I. INTRODUCTION

The evidence for the existence of dark matter in various astrophysical systems has been gathering over the past three decades. It is now well-recognized that the presence of dark matter is required in order to explain the observations of galaxies and other astrophysical systems on larger scales. The clearest support for the existence of dark matter comes from the now well-known observation of nearly flat rotation curves or constant rotation velocity in the outer parts of galaxies \cite{1,2}. Surprisingly the rotation velocity is observed to remain nearly constant till the last point at which it can be measured. The simple principle of rotational equilibrium then tells one that the amount of dark to visible mass must increase at larger radii. Thus the existence of the dark matter is deduced from its dynamical effect on the visible matter, namely the stars and the interstellar gas in galaxies.

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The presence of dark matter in the elliptical galaxies is more problematic to ascertain since these do not contain much interstellar hydrogen gas which could be used as a tracer of their dynamics, and also because these galaxies are not rotationally supported. These galaxies are instead supported by pressure or random motion of stars. Thus, here the motions of planetary nebulae which arise from old, evolved stars, as well as lensing, have been used to trace the dark matter \[3\]. The fraction of dark matter at four effective radii is still uncertain with values ranging from 20% to 60% given in the literature, for the extensively studied elliptical galaxy NGC 3379 \[4\].

The currently popular scenario of galaxy formation, based on the ΛCDM model (described below), predicts a universal profile for the dark matter for galaxies \[5\]. While this model was initially successful, over the years many discrepancies between the predictions from it and the observations have been pointed out. The strongest one has been the ‘cusp-core’ issue of the central mass distribution. While Navarro et. al \[5\] predict a cuspy central mass distribution, the observations of rotation curves of central regions of galaxies, especially the low surface brightness galaxies, when modeled show a flat or cored density distribution \[6\].

Historically the first evidence for the unseen or dark matter was found in clusters of galaxies. Assuming the cluster to be in a virial equilibrium, the total or the virial mass can be deduced from the observed kinematics. Zwicky \[7\] noted that there is a discrepancy of a factor of \(~10\) between the observed mass in clusters of galaxies and the virial mass deduced from the kinematics. In other words, the random motions are too large for the cluster to be bound and a substantial amount of dark matter \(~10\) times the visible matter in galaxies is needed for the clusters of galaxies to remain bound. This discrepancy remained a puzzle for over four decades, and was only realized to be a part of the general trend after the galactic-scale dark matter was discovered in the late 1970’s.

On much larger cosmological scales there as been some evidence for non-baryonic dark matter from Big Bang Nucleosynthesis and other cosmological data. However, the recent high precision determination of the cosmological parameters using Type I supernova data \[8\] as well as precise mapping of the cosmic microwave background radiation (CMBR) by the WMAP collaboration \[9, 10\] has pinpointed the total relic dark matter density in the early universe. Accordingly, dark matter forms almost 26% of all the matter density of the universe, with visible matter about 4% and the dark energy roughly about 70% of the total energy density. This goes under the name of ΛCDM model with Λ standing for dark energy and denoted by the Einstein’s constant, and CDM standing for Cold Dark Matter.

Despite the fact that the existence of dark matter has been postulated for over three decades,
there is still no consensus of what its constituents are. This is summarized well in many review articles [11, 12] for reviews that span early to recent times in this topic.

The baryonic dark matter in the form of low-mass stars, binary stars, or Jupiter-like massive planets were ruled out early on (see [11] for a summary). At the amount of dark matter required to explain the flat rotation curves, the number densities required of these possible constituents would be large, and hence it would be hard to hide these. If present in these forms, they should have been detected either from their absorption or from their emission signals. It has also been proposed that the galactic dark matter could be in the form of dense, cold molecular clumps [13], though this has not yet been detected. This alternative cannot be expected to explain the dark matter necessary to explain the observations of clusters, or indeed the elliptical galaxies since the latter have very little interstellar gas.

From a more fundamental point of view, it is not clear what kind of elementary particle could form dark matter. The standard model of particle physics describes all matter to be made up of quarks and leptons of which neutrinos are the only ones which can play the role of dark matter as they are electrically neutral. However with the present indications putting the neutrino masses in the range $\lesssim 1$ eV they will not form significant amount of dark matter. On the other hand, there could be sterile neutrinos with masses of the order of keV-MeV which could form warm dark matter. However the warm dark matter has been increasingly been disfavored over the years by the experimental data.

While the Standard Model itself cannot accommodate a candidate for dark matter, most theories which are extensions of the Standard Model contain a candidate for dark matter. It should be noted that most of these extensions have been constructed for reasons other than explaining dark matter. A few examples of these theories and the corresponding candidates for dark matter are as follows. (i) Axions are pseudo-scalar particles which appear in theories with Peccei-Quinn symmetry, proposed as solution to the strong CP problem of the standard model. They also appear in String theories. The present limits on axions are [14] extremely strong from astrophysical data. In spite of this, there is still room for axions to form a significant part of the dark matter relic density. (ii) Supersymmetric theories which incorporate fermion-boson interchange symmetry are proposed as extensions of Standard Model to protect the Higgs mass from large radiative corrections. These models have several candidates for a dark matter particle depending on how supersymmetry is broken [15]. The supersymmetric partners of $Z/\gamma$ bosons called neutralino, or the graviton called the gravitino, and even the axion (either the scalar saxion or the fermionic axino) can reasonably
explain the observed dark matter relic density. (iii) Other classic extensions of the Standard Models either based on large extra dimensions or symmetries which incorporate the Higgs as a pseudo-Goldstone boson also have dark matter candidates. In both versions of the extra dimensional models, i.e., the Arkani-Hamed, Dimopoulos, Dvali (ADD) \[16, 17\] and Randall-Sundrum (RS) \[18, 19\], models, the lightest Kaluza-Klein particle can be considered as the dark matter candidate \[20, 21, 22, 23\]. Similarly, in the little-Higgs models where the Higgs boson is a pseudo-Goldstone boson of a much larger symmetry, a symmetry called T-parity \[24\] assures us a stable and neutral particle which can form the dark matter. In the recent years, there has also been some discussion about the possibilities of dark matter consisting of not one particle but two particles. This goes under the name of ‘two-component dark matter’ \[25\]. Some extensions of Standard Model do have such situations lending theoretical support to these ideas.

II. THE DATA

If the dark matter candidate is indeed a new particle and it has interactions other than gravitational interactions, then the most probable interactions it could have is the weak interactions\(^1\). This weakly interacting particle, dubbed as WIMP (Weakly Interacting Massive Particle) could interact with ordinary matter and leave traces of its nature. There are two ways in which the WIMP could be detected (a) Direct Detection: Here one looks for the interaction of the WIMP with matter directly; WIMPs which are present all over the Galaxy can scatter off nuclei, one can then try to measure the recoil of the nuclei and from there infer the properties of the WIMP. This scattering cross section would depend on whether it was elastic or inelastic and further on the spin of the WIMP. There are more than 20 experiments located all over the world, which are currently looking for WIMP through this technique. Some of them are DAMA, CDMS, CREST, CUORICINO, DRIFT etc. (b) Indirect detection: Since WIMPs are charge-less they can be their own antiparticles. In such a case, when WIMPs cluster together, they can annihilate with themselves giving rise to electron-positron pairs, gamma rays, proton-anti-proton pairs, neutrinos etc. The flux of such radiation is directly proportional to the annihilation rate, which further is dependent on the dark matter density. Observation of this radiation could lead to information about the masses

\(^1\) It cannot have electromagnetic interactions as this would mean it is charged, and it cannot have strong interactions as this would most likely mean it would be baryonic in form - both these prospects are already ruled out by experiments.
and the cross section strengths of the WIMPs. Currently, there are several experiments which are looking for this radiation (i) MAGIC, HESS, CANGAROO, FERMI/GLAST, EGRET etc look for the gamma ray photons (ii)HEAT, CAPRICE, BESS, PAMELA, AMS, GLAST can also see anti-protons. (iii) High energetic neutrinos are observed by AMANDA, ANTARES, ICECUBE etc (for a more detailed discussion see [14]).

Over the years, there have been indications of the presence of dark matter through indirect experiments. The most popular of the these indications were INTEGRAL and DAMA results [26]. But, none of them could catch the imagination of the community as the present set of experiments have managed to do. This is because for the first time it appears as though several experiments are seeing the same effect. These new experiments are based on advanced technology and improved statistics, and the reports of their results in the recent months have led to a lot of excitement in this field. Furthermore, given that these results significantly differ from the expectations, they indicate some yet non-understood physics being operative within the vicinity of our Galaxy. The four main experiments which have led to this excitement are (i) PAMELA[27] (ii) ATIC[28] (iii) HESS[29] and (iv) FERMI[30]. All of these experiments involve international collaborations spanning several nations. While PAMELA and FERMI are satellite based experiments, ATIC is a balloon borne experiment and HESS is a ground based telescope.

The satellite-based Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics or PAMELA collects cosmic ray protons, anti-protons, electrons, positrons and also light nuclei like Helium and anti-Helium. One of the main strengths of PAMELA is that it could distinguish between electrons and anti-electrons, protons and anti-protons and measure their energies accurately. The sensitivity of the experiment in the positron channel is up to approximately 300 GeV and in the anti-proton channel up to approximately 200 GeV. Since it was launched in June 2006, it was placed in an elliptical orbit at an altitude ranging between 350 – 610 km with an inclination of 70.0°. About 500 days of data was analyzed and recently presented. The present data is from 1.5 GeV to 100 GeV has been published in the journal Nature recently. In this paper, PAMELA reported an excess of positron flux compared to earlier experiments. In the left panel of the Fig. 1, we see PAMELA results along with the other existing results. The y-axis is given by \( \phi(e^+/\phi(e^-) + \phi(e^+)) \), which \( \phi \) represents the flux of the corresponding particle. According to the analysis presented by PAMELA, the results of PAMELA are consistent with the earlier experiments up to 20 GeV, taking into consideration the solar modulations between the times of PAMELA and previous experiments. Particles with energies up to 20 GeV are strongly effected by
FIG. 1: Results from PAMELA and ATIC with theoretical models. The left panel shows PAMELA\cite{27} positron fraction along with theoretical model. The solid black line shows a calculation by Moskalenko & Strong\cite{31} for pure secondary production of positrons during the propagation of cosmic-rays in the Galaxy. The right panel shows the differential electron energy spectrum measured by ATIC\cite{28} (red filled circles) compared with other experiments and also with theoretical prediction using the GALPROP\cite{32} code (solid line). The other data points are from AMS\cite{33}(green stars), HEAT\cite{34} (open black triangles), BETS\cite{35} (open blue circles), PPB-BETS\cite{36} (blue crosses) and emulsion chambers (black open diamonds) and the dashed curve at the beginning is the spectrum of solar modulated electron. All the data points have uncertainties of one standard deviation. The ATIC spectrum is scaled by $E_e^{3.0}$. The figures of PAMELA and ATIC are reproduced from their original papers cited above.

Solar wind activity which varies with the solar cycle. On the other hand, PAMELA has data from 10 GeV to 100 GeV, which sees an increase in the positron flux. The only other experimental data in this energy regime (up to 40 GeV) are the AMS and HEAT, which while having large errors are consistent with the excess seen by PAMELA.

Cosmic ray positrons at these energies are expected to be from secondary sources i.e as result of interactions of primary cosmic rays (mainly protons and electrons) with interstellar medium. The flux of this secondary sources can be estimated by numerical simulations; the most popular package goes under the name GALPROP. In the left panel of Fig. 1 the expectations based on GALPROP are given as a solid line running across the figure. From the figure it is obvious that PAMELA results show that the positron fraction increases with energy compared to what GALPROP expects. These indicate that the positron excess could be a result of a primary source rather than a secondary source. This primary source could be either dark matter decay/annihilation or a nearby astrophysical object like a pulsar. Before going to the details of the interpretations,
FIG. 2: The Fermi LAT CR electron spectrum. The red filled circles shows the data from Fermi along with the gray bands showing systematic errors. The dashed line correspond to a theoretical model by Mosalenko et al. [37]. The figure of FERMI is reproduced from their original paper cited above.

let us summarize the results from ATIC and FERMI too.

**Advanced Thin Ionization Calorimeter** or in short ATIC is a balloon-borne experiment to measure energy spectrum of individual cosmic ray elements within the region of GeV up to almost a TeV (thousand GeV) with high precision. This experiment was designed to be a high-resolution and high statistics experiment in this energy regime compared to the earlier ones. ATIC (right panel in Fig. [1]) measures all the cosmic ray components electrons, protons (and their anti-particles) with high energy resolution. It can also distinguish well between electrons and protons. ATIC presented its primary cosmic ray electron ($e^- + e^+$) spectrum between the energies 3 GeV to about 2.5 TeV$^2$. The results show that while the spectrum up to 100 GeV agrees with the expectations based on the GALPROP simulation for primary electron spectrum, show a sharp increase above 100 GeV. In fact, the total flux increases till about 600 GeV where it peaks and then sharply falls to about 800 GeV. Thus, ATIC is an excess of the primary cosmic ray ($e^- + e^+$) spectrum between the

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$^2$ The cosmic ray electrons follow a power law spectrum, the index being $\sim -3.0$. Thus it is normalised by a factor $E^{3.0}$. 
energy range $300 - 800$ GeV. The rest of the spectrum is consistent with the expectations within the errors. What is interesting about such peaks in the spectrum are that if they are confirmed they could point towards a resonance in dark matter annihilation cross section. Another ground based experiment sensitive to cosmic rays within this energy range is H.E.S.S which can measure gamma rays from few hundred GeV to few TeV. This large reflecting array telescope operating from Namibia has presented data from $>600$ GeV to about 5 TeV. While it could confirm neither the ‘peaking’ at like behavior at 600 GeV nor the sharp cut-off at 800 GeV of the ATIC data, with an over all energy uncertainty of 15% in the HESS data, the results of ATIC seems to be consistent with that of HESS, though it does not confirm with any of the sharp (rise or fall) features of the ATIC spectrum.

The Large Area Telescope (LAT) is one of the main components of the Fermi Gamma Ray Space Telescope, which was launched in June 2008. Due to its high resolution and high statistical capabilities, it has been one of the most anticipated experiments in the recent times. Fermi can measure Gamma rays between 20 MeV and 300 GeV with high accuracy and primary cosmic ray electron ($e^- + e^+$) flux between 20 GeV and 1 TeV, again with high resolution and high statistics. The FERMI-LAT collaboration has recently published its six month data on the primary cosmic ray electron flux. In Fig. 2 we reproduce the result produced by the FERMI collaboration. They find that the primary cosmic ray electron spectrum more or less goes along the expected lines up to 100 GeV (its slightly below the expected flux between 10 and 50 GeV), however above 100 GeV, there is strong signal for an excess of the flux ranging up to 1 TeV. The FERMI data thus confirms the excess in the electron spectrum which was seen by ATIC, the excess however has a much flatter profile.

**III. THE INTERPRETATIONS**

Any interpretation must be able to explain the following experimental observations [38]:

- The excess in the positron fraction measured by PAMELA up to 100 GeV.
- The lack of excess in the anti-proton fraction measured by PAMELA up to 100 GeV.
- The excess in the total $e^- + e^+$ spectrum above 100 GeV seen by FERMI, HESS, etc. While below 100 GeV, the measurements have been consistent with GALPROP expectations.
- The absence of sharp features in the total electron spectrum measured by FERMI etc.
Two main interpretations have been put forward: (a) A nearby astrophysical source which has a mechanism to accelerate particles to high energy and (b) A dark matter particle which decays or annihilates leading to excess of electron and positron flux. The interesting aspect is that which of the interpretations is valid will be known within the coming years with enhanced data from both PAMELA and FERMI. Let us now turn to both the interpretations:

Pulsars and supernova shocks have been proposed as likely astrophysical local sources of energetic particles that could explain the observed excess of the positron fraction \[39, 40\]. In the high magnetic fields present in the pulsar magnetosphere, electrons can be accelerated and induce an electromagnetic cascade through the emission of curvature radiation. This can lead to a production of high energy photons above the threshold for pair production; and on combining with the number density of pulsars in the Galaxy, the resulting emission can explain the observed positron excess \[39\]. The energy of the positrons tell us about the site of their origin and their propagation history \[41\]. The cosmic ray positrons above 1 Tev could be primary and arise due to a source like a young pulsar within a distance of 100 pc \[42\]. This would also naturally explain the observed anisotropy, as argued for two of the nearest pulsars, namely B0656+14 and the Geminga \[43, 44\]. Diffusive shocks as in a supernova remnant hardens the spectrum, hence this process can explain the observed positron excess above 10Gev as seen from PAMELA \[45\]. Future data from Fermi on directionality will help identify between pulsars/supernova shocks, and the dark matter annihilation, as two different kinds of sources of the observed cosmic ray positron spectrum.

Another possible astrophysical source that has been proposed is the pion production during acceleration of hadronic cosmic rays in the local sources \[40\]. It has been argued \[46\] that the measurement of secondary nuclei produced by cosmic ray spallation can confirm whether this process or pulsars are more important as the production mechanism. They show that the present data from ATIC-II supports the hadronic model and can account for the entire positron excess observed.

If the excess observed by PAMELA, HESS and FERMI is not due to some yet not fully-understood astrophysics but is a signature of the dark matter, then there are two main processes through which such an excess can occur:

(i) The annihilation of dark matter particles into Standard Model (SM) particles and

(ii) The decay of the dark matter particle into SM particles.
In the case of annihilating dark matter the observed excess would set a limit on the cross-section times the velocity of the dark matter particle. Given that the same process would also occur in the early universe with particles traveling at velocities much higher (about 1000 times the particle velocities in galaxies), the observed dark matter relic density of the universe is not compatible with this interpretation. Avoiding this conflict by considering the non-thermal production of dark matter in early universe, and further considering a very heavy dark matter $\sim \mathcal{O}(2 - 3)$ TeV to explain the absence of excess in anti-proton channel etc, have not improved the situation. The results from FERMI have no sharp features in the total electron spectrum, which have rendered these interpretations non-compatible with the data. However, a recent analysis of the FERMI data taking into account possible variations in the astrophysical background profile due to presence of local cosmic ray accelerator has shown that it is possible to explain the observed excess with annihilating dark matter even within the sub-TeV region [47, 48, 49, 50] and as low as 30 – 40 GeV [51]. Some more detailed analysis can be found in [52].

Several existing models of annihilating dark matter become highly constrained or ruled out if one requires to explain PAMELA/ATIC and FERMI data. The popular supersymmetric DM candidate neutralino with its annihilating partners such as chargino, stop, stau etc, can explain the cosmological relic density but not the excess observed by PAMELA/ATIC. Novel models involving a new ‘dark force’, with a gauge boson having mass of about 1 GeV [53], which predominantly decays to leptons, together with a mechanism called Sommerfeld enhancement seem to fit the data well. The above class of models, which are extensions of standard model with an additional $U(1)$ gauge group, caught the imagination of the theorists [54, 55, 56, 57]. A similar supersymmetric version of this mechanism where the neutralinos in the MSSM can annihilate to a scalar particle, which can then decay the observed excess in the cosmic ray data [58]. Models involving Type II seesaw mechanism [59] have also been considered recently where neutrino mass generation is linked with the positron excess. In addition to the above it has been shown that extra dimensional models with KK gravitions can also produce the excess [60]. Models based on Nambu-Goldstone Dark Matter have been studied in [61].

In the case of decaying dark matter, the relic density constraint of the early universe is not applicable, however, the lifetime of the dark matter particle (typically of a mass of $\mathcal{O}(1)$ TeV) should be much much larger than ($\sim 10^9$ times) the age of the universe [38]. Such a particle can fit the data well. A crucial difference in this picture with respect to the annihilation picture is that the decay rate is directly proportional to the density of the dark matter $\rho$, whereas the annihilation rate is
proportional to its square, $\rho^2$. The most promising candidates in the decaying dark matter seem to be a fermion (scalar) particle decaying into $W^\pm l^\pm$ etc. ($W^+W^-$ etc.) \[62, 63, 64, 65\]. The popular models of decaying dark matter having gravitino, with small $R$-parity violation which in turn makes it unstable, as the candidate is also promising \[66\]. A heavy neutralino with $R$-parity violation can also play a similar role \[67\] stated above. A recent more general model independent analysis has shown that, assuming the GALPROP background, gravitino decays cannot simultaneously explain both PAMELA and FERMI excess. However, the presence of additional astrophysical sources can change the situation \[68\]. Independent of the gravitino model, it has been pointed out that, the decays of the Dark Matter particle could be new signals for unification where the Dark Matter candidate decays through dimension six operators suppressed by two powers of GUT scale \[69, 70, 71\].

An interesting aspect about the present situation is that, future data from PAMELA and FERMI could distinguish whether the astrophysical interpretation i.e. in terms of pulsars or the particle physics interpretation in terms of dark matter is valid \[72\]. PAMELA is sensitive to up to 300 GeV in its positron fraction and this together with the measurement of the total electron spectrum can strongly effect the dark matter interpretations. FERMI with its improved statistics, can on the other hand look for anisotropies within its data \[73\] which can exist if the pulsars are the origin of this excess. Further measurements of the anti-Deuteron could possibly gives us a hint why there is no excess in the anti-Proton channel \[74\].

In the present note, we have tried to convey exciting developments which have been happening recently within the interface of astrophysics and particle physics, especially on the one of the most intriguing subjects of our time, namely, the Dark Matter. Our note is not by any yard stick a review on this topic, we have only cited some papers out of the many interesting works present in the recent literature so as to convey the main points and the excitement to both the astrophysicists and particle physicists alike. Our sincere apologies to all those authors whose works we have omitted.

Acknowledgments

We thank PAMELA collaboration, ATIC collaboration and FERMI-LAT collaboration for giving us permission to reproduce their figures. We thank Diptiman Sen for a careful reading of this article and useful comments. C.J. would like to thank Gary Mamon for illuminating discussions
regarding the search for dark matter in elliptical galaxies and clusters.

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