Nuclear Instruments and Methods in Physics Research A 630 (2011) 48–51

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Possible interpretations of the high energy cosmic ray electron spectrum measured with the Fermi space telescope

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ARTICLE INFO

Available online 15 June 2010

Keywords:
Fermi-LAT
Cosmic rays electrons
Pulsars
Dark matter

ABSTRACT

The Fermi Large Area Telescope (LAT) recently measured the cosmic ray electrons-plus-positrons (CRE) spectrum between 20 GeV and 1 TeV. In this contribution we discuss several interpretations of those measurements in combination with other experimental data. We show that, as far as concerns the reported Fermi-LAT data alone, a simple interpretation invoking a single class of astrophysical electron sources is possible. If, however, also the CRE spectrum measured by H.E.S.S. and especially the positron fraction reported by PAMELA are accounted, that scenario fails to provide a combined description of those results. Rather, we show that several combinations of parameters, involving $e^{\pm}$ pair emission by pulsars or dark matter annihilation, allow a consistent interpretation of all data sets.

1. Introduction

The Fermi collaboration recently provided a very accurate measurement of the cosmic ray electron (CRE) (unless explicitly otherwise stated we define electrons to be electrons plus positrons in this contribution) spectrum from 20 GeV to 1 TeV performed with its Large Area Telescope (LAT) [1]. A simple power law fit of the Fermi-LAT electron energy spectrum (see Fig. 1) is possible giving: $J_{e^{\pm}} = (175.40 \pm 6.09)(E/1\,\text{GeV})^{-(3.045 \pm 0.008)}$ $\text{GeV}^{-1}\,\text{m}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$ with $\chi^2 = 9.7$ (for 23 d.o.f.) where statistical and systematic errors have been, conservatively, added in quadrature.

This is significantly harder than the electron spectrum measured from other experiments before 2008. Indeed, the measurements performed by several balloon-born experiments [2] and the AMS-01 space mission [3] were compatible with a featureless power law spectrum with an index close to -3.2. More recently, and before Fermi-LAT, the ATIC balloon experiment also measured the CRE spectrum between 20 GeV and 2 TeV [4]. While below 100 GeV ATIC and Fermi-LAT are in good agreement, at high energies ATIC found a prominent spectral feature peaked between 300 and 600 GeV which was not observed by Fermi-LAT. Furthermore, the H.E.S.S. (Aharonian et al., 2008, 2009 [5,6]) atmospheric Cherenkov telescope measured the electron spectrum in the 340 GeV–5 TeV energy range. H.E.S.S. data are in agreement with Fermi-LAT within their systematic uncertainties and reveal a significant steepening of the CRE spectrum above $\sim$1 TeV. It is interesting to observe, that the spectrum measured by Fermi-LAT is consistent, within systematic

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doi:10.1016/j.nima.2010.06.024

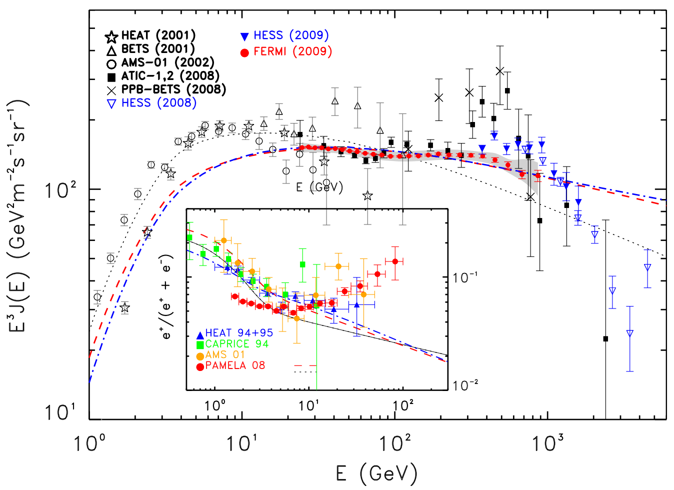

Fig. 1. Fermi-LAT CRE data [1], as well as several other experimental data sets, are compared to the e^-+e^+ spectrum modeled with GALPROP. The gray band represents systematic errors on the CRE spectrum measured by Fermi-LAT. The dotted (black) line corresponds to the conventional model used in Ref. [11] to fit pre-Fermi data conventional model. The dashed (red) and dash-dotter (blue) lines are obtained with modified injection indexes $\gamma_0 = 2.42$ (for $\delta = 0.33$) and $\gamma_0 = 2.33$ (for $\delta = 0.6$), respectively. In the insert the positron fraction for the same models is compared with experimental data. All models account for solar modulation in the force field approximation assuming a potential $\Phi = 0.55$ GV. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

errors, with a hardening at around 70 GeV and a steepening above ~ 500 GeV. Although the significance of those features is very low within current systematics, they suggest that more components in the electron high energy spectrum may be present.

Another independent indication of the presence of a possible deviation from the standard picture came from the recent measurements of the positron to electron fraction, $e^+/(e^- + e^+)$, between 1.5 and 100 GeV by the PAMELA satellite experiment [7,8]. PAMELA found that the positron fraction changes slope at around 10 GeV and begins to increase steadily up to 100 GeV. This behaviour is very different from that predicted for secondary positrons produced in the collision of CR nuclides with the interstellar medium (ISM).

It is also worth noticing that the hard electron spectrum observed by Fermi-LAT exacerbates the discrepancy between the predictions of standard CR theoretical models and the positron faction excess measured, most conclusively, by PAMELA [7,8]. This makes the exploration of some non-standard interpretations more compelling.

In this contribution we will first consider a standard interpretation of the Fermi-LAT results invoking a single primary component of the electrons (e^-) produced by Galactic supernova remnants (SNR's). We will show that although this scenario allows a satisfactory description of Fermi-LAT data it fails to provide a consistent interpretation of PAMELA and H.E.S.S. experimental results. Then, we will then consider two alternative scenarios where Galactic pulsars or annihilating dark matter may give rise to additional electron and positron components which allow to consistently interpret all available data sets.

2. Single component interpretation

We start considering a possible interpretation of Fermi-LAT CRE data in terms of a conventional *Galactic CR electron scenario* (GCRE) model assuming that electron sources are continuously distributed in the Galactic disk and that positrons are only produced by the collision of primary CR nuclides with the interstellar gas.

To this purpose we use the GALPROP numerical CR propagation code [9]. We consider here two reference conventional models with injection spectral index $\gamma_0 = 2.42$ above 4 GeV, if the value of power law index of the diffusion coefficient dependence on energy is $\delta = 0.33$, and $\gamma_0 = 2.33$ if $\delta = 0.6$ (see Table 1 in Ref. [10] for more details about those models). As shown in Fig. 1 these models provide a good representation of Fermi-LAT CRE data. In the same figure we also show for comparison a conventional model with $\gamma_0 = 2.54$ which was already successfully used to interpret pre-Fermi CRE data [11] and the diffuse gamma-ray emission measured by Fermi-LAT at intermediate Galactic latitudes [12].

GCRE models, however, face a series of problems, when compared with other experimental data sets, namely (i) they display a significant tension with respect to low energy pre-Fermi data, AMS-01 [3] and HEAT [14] most noticeably; (ii) they exceed H.E.S.S. data above 1 TeV; (iii) most seriously, the positron fraction $e^+/(e^+ + e^-)$ they predict is not consistent with that measured by PAMELA [7,8] (see the insert in Fig. 1). While item (ii) may be interpreted as a consequence of the stochastic nature of astrophysical sources [13] the other caveats are most serious.

3. Pulsar interpretation

Pulsars are undisputed sources of relativistic electrons and positrons, believed to be produced in their magnetosphere and subsequently possibly reaccelerated by the pulsar wind or in the supernova remnant shocks (see, e.g. [15,16]). For bright young pulsars the maximal acceleration energy can be as large as 10^3 TeV. This quantity decreases for middle-age or, so called, *mature* pulsars (i.e. with age $10^4 \lesssim T \lesssim 10^6$ yr). Electrons and positrons are expected to be liberated into the ISM only after pulsar wind nebulae merge into the ISM, or the pulsar leaves the nebula due to its proper motion, 10^4–10^5 yr after the pulsar birth. Most of the emission takes on a time scale much shorter than the propagation time to the Earth, so that *mature* pulsars can effectively be treated as burst-like sources of electrons and positrons. The possible role of these sources explaining the PAMELA positron fraction anomaly [7,8] has been discussed in several papers (see, e.g. [16–18] and Refs. therein).

We computed the spectrum of electrons and positrons from each pulsar by following the approach reported in the appendix of [10]. The basic input is the $e^\pm$ energy release of each mature pulsar that we determine by integrating the observed spin-down luminosity over time giving (see, e.g. [18]) $E_{e^\pm} \simeq \eta_{e^\pm} \dot{E}_{\rm PSD} T^2/\tau_0$ where $\dot{E}_{\rm PSD}$ is the present time spin-down luminosity determined form the observed pulsar timing, $T = P/2\dot{P}$ (where P is the pulsar period) the pulsar age, and $\eta_{e^\pm}$ is the $e^\pm$ pair conversion efficiency of the radiated electro-magnetic energy. For the characteristic luminosity decay time we assume $\tau_0 = 10^4$ yr as conventionally adopted for mature pulsars. The setup we use here to model the large-scale GCRE spectrum is a slightly rescaled version of the conventional model used to interpret pre-Fermi data [11] (we reduced the electron flux normalization by a factor ~ 0.95 respect to that model so to leave room to the extra pulsar $e^\pm$ component).

In general several pulsars contribute to the electron and positron fluxes reaching the Earth. For this reason we summed the contribution to the electron and positron flux of all pulsars in ATNF radio pulsar catalogue (http://www.atnf.csiro.au/research/pulsar/psrcat/) [19] with distance $d < 3$ kpc and age $T > 5 \times 10^4$ yr (~ 150 pulsars). More distant pulsars give a negligible contribution at the energies considered here; we

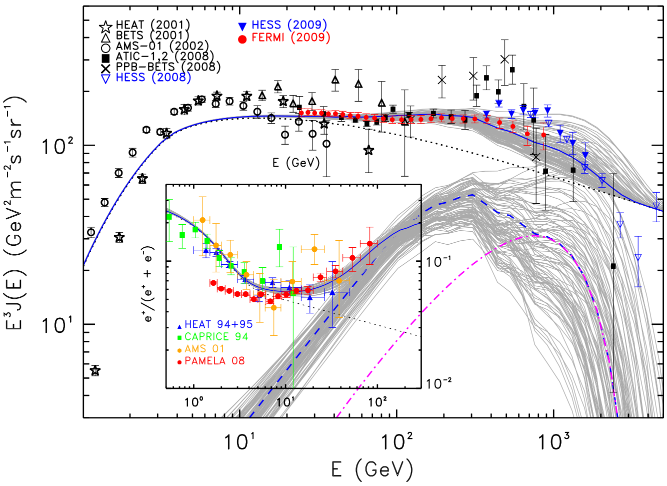

Fig. 2. The e^-+e^+ spectrum from pulsars plus the Galactic (GCRE) component with experimental data (dotted line). Each gray line represents the sum of all pulsars for a particular combination of pulsar parameters. The dashed (pulsars only) and solid (pulsars+GCRE component) blue lines correspond to a representative choice among that set of possible realizations. The dot-dashed (purple) line represents the contribution of Monogem pulsar in that particular case. Note that for graphical reasons here Fermi-LAT statistical and systematic errors are added in quadrature. In the insert the positron fraction for the same models is compared with experimental data. Solar modulation is accounted as done in Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

assume that electron accelerated in younger pulsars are still confined in their nebulae (lowering this limiting age would not change significantly our results). For each of these pulsars we use the spin-down luminosity given in the catalogue and randomly vary the relevant parameter in the following representative ranges: $800 < E_{cut} < 1400\,\text{GeV}$, $10 < \eta_{e^\pm} < 30\%$ and $5 < (\Delta t/10^4\,\text{yr}) < 10$ and $1.5 < \Gamma < 1.9$. These ranges of parameter are compatible with our observational and theoretical knowledge of particle acceleration in PWNe (see, e.g. [20]). Following this approach we find that Fermi-LAT CRE data comfortably lie within the bands of those realizations (see Fig. 2) and are in reasonable agreement with the positron fraction measured by PAMELA (see the insert in the same figure). It should be noted that the ATFN catalogue does not include all pulsars. Some pulsars radio beams are not pointing toward us and also selection effects in the radio detection intervene to reduce the number of the observed pulsars. Furthermore, the recent discovery of a population of radio-quiet gamma-ray pulsars by Fermi-LAT [21] has demonstrated that those pulsars are a significant fraction of the total pulsar set. We do not expect, however, that the average spectral shape would change significantly by accounting for pulsars not included in the ATFN catalogue. The larger electron and positron primary flux due to the contribution of those sources can be compensated by invoking a smaller pair conversion efficiency $\eta_{e^\pm}$ making this scenario even more appealing. While selection effects may lead to underestimate older pulsar at large distance, their role is almost negligible at the energies of interest here.

4. Dark matter interpretation

Here we briefly discuss about the alternative possibility of interpreting in Fermi-LAT CRE data in terms of an electron and positron component originated from the pair-annihilation of Galactic dark matter (DM). The new Fermi-LAT data affect a dark matter interpretation of CRE data in at least three ways: (i) The rationale to postulate a particle dark matter mass in the 0.5–1 TeV range, previously motivated by the ATIC data and the detected "bump", is now much weaker, if at all existent, with the high statistics Fermi-LAT data; (ii) CRE data can be used, in the context of particle dark matter model building, to set constraints on the pair-annihilation rate or on the decay rate, for a given dark matter mass, diffusion setup and Galactic halo model; (iii) as discussed in Section 2, unlike the Fermi-LAT CRE result, the PAMELA positron fraction measurement requires one or more additional primary sources in addition to the standard GCRE component, as discussed in Section 2; if the PAMELA data are interpreted in the context of a dark matter related scenario, Fermi-LAT data provide a correlated constraint to the resulting total CRE flux.

Here we consider the following representative class of models:

1. *Pure $e^\pm$ models*: For this class of models, the dark matter pair-annihilation always yields a pair of monochromatic $e^\pm$, with injection energies equal to the mass of the annihilating dark matter particle. Such models arise for instance in the context of frameworks where the dark matter sector is *secluded* [22], and the dark matter pair-annihilates into a *light gauge boson* which can then kinematically decay only into $e^\pm$ [23].
2. *Lepto-philic models*: Here we assume a democratic dark matter pair-annihilation branching ratio into each charged lepton species: 1/3 into $e^\pm$, 1/3 into $\mu^\pm$ and 1/3 into $\tau^\pm$. Here too antiprotons are not produced in dark matter pair-annihilation. Examples of models where the leptonic channels largely dominate include frameworks where either a discrete symmetry or the new physics mass spectrum suppresses other annihilation channels [24,25].
3. *Super-heavy dark matter models*: As pointed out in [26], antiprotons can be suppressed below the PAMELA measured flux if the dark matter particle is heavy (i.e. in the multi-TeV mass range), and pair-annihilates, e.g. in weak interaction gauge bosons. Models with super-heavy dark matter can have the right thermal relic abundance, e.g. in the context of the minimal supersymmetric extension of the Standard Model, as shown [27].

For those models the flux of antiprotons is generically suppressed to a level compatible with experimental data. For the three classes of models outlined above, we consider here the same large scale Galactic CR electron and positron spectrum adopted in Section 3. From Fig. 3 we see that lepto-philic models allow a reasonable fit

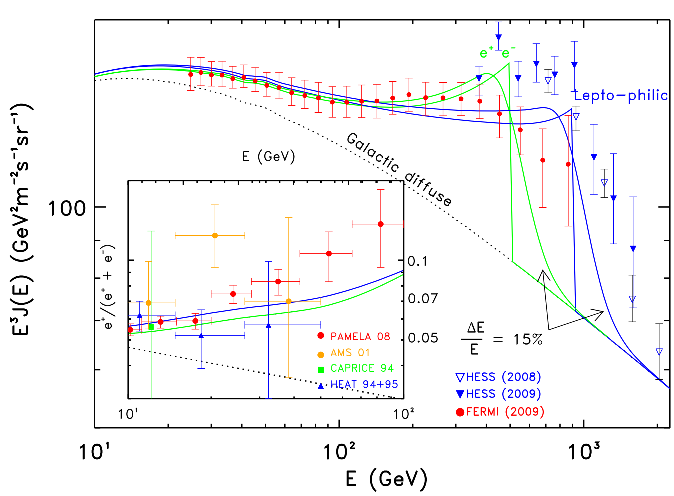

Fig. 3. Predictions for the CRE data from three benchmark dark matter models, and current measurements. The same large-scale Galactic CRE components (dotted line) as in Fig. 2 is used here. Statistical and systematic errors on Fermi-LAT data are added in quadrature. In the insert the positron fraction for the same models is compared with experimental data. For purely illustrative purposes, for each DM model we show both theoretical and smeared spectra obtained by accounting for a 15% energy resolution.

of Fermi-LAT, H.E.S.S. as well as PAMELA data while pure $e^{\pm}$ model seems to be disfavored (though not excluded on the basis of the analysis reported in Ref. [10]). Rather, the super-heavy dark matter models are significantly disfavored by Fermi-LAT and H.E.S.S. CRE data. The preferred range for the dark matter mass lies between 400 GeV and 1–2 TeV, with larger masses increasingly constrained by the H.E.S.S. results [5,6]. The required annihilation rates, when employing a conventional dark matter density profile (see Ref. [10] for details), imply typical boost factors ranging between 20 and 100, when compared to the value $\langle \sigma v \rangle \sim 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$ expected for a thermally produced dark matter particle relic.

Notice that other dark matter models (including, e.g. TeV-scale dark matter particles annihilating in muon-antimuon final states, either monochromatically or through the decays of intermediate particles) offer additional possible case-studies, as discussed, e.g. in Ref. [28,29].

5. Conclusions

We reported on possible interpretations for the cosmic ray electron-plus-positron (CRE) spectrum measured by Fermi-LAT. The measured CRE flux is significantly harder than previously believed, and it does not show any sharp feature in the multi-hundred GeV range, although there are hints of an extra-component between 100 GeV and 1 TeV.

In the context of astrophysical interpretations to the CRE data, we discussed in the present analysis the case of a single large-scale diffuse Galactic (GCRE) component, and a two-component scenario which adds to the GCRE flux a primary electron and positron component produced by mature pulsars. In the GCRE scenario, a spatially continuous distribution of primary CRE sources in the Galactic disk, provides a satisfactory explanation to the Fermi-LAT CRE data for several combinations of the injection spectral index γ_0 and the CR propagation parameters. This scenario, however, is in sharp tension with the PAMELA data on the positron fraction, more than previously considered in the framework of GCRE models, as a consequence of the hardness of the electron-plus-positron spectrum measured by Fermi-LAT. Furthermore, a tension is also present between these GCRE models fitting the Fermi-LAT CRE spectrum and pre-Fermi experimental data below 10 GeV and H.E.S.S. CRE data above the TeV. Taking into account nearby mature pulsars as additional sources of high-energy CRE, we showed that both the PAMELA positron excess and the Fermi CRE data are naturally explained by known objects.

We also briefly considered another possible primary source of high-energy CRE: the annihilation or decay of particle dark matter in the Galactic halo. Fermi-LAT CRE data do not confirm the sharp spectral feature in the 500–1000 GeV range that prompted several studies to consider a dark matter particle mass in that same range. Yet, we showed that a dark matter particle annihilating or decaying dominantly in leptonic channels, and with a mass between 400 GeV and 2 TeV is compatible with both the positron excess reported by PAMELA and with the CRE spectrum measured by Fermi-LAT.

While we found that the pulsar interpretation seems to be favored by Fermi-LAT CRE data, a clear discrimination between this and the dark matter scenario is not possible on the basis of the currently available data and may require to consider complementary observations. Most relevant Fermi measurements in this framework will be (i) extend the energy range both to lower and to higher energies than reported so far, (ii) allow anisotropy studies of the arrival direction of high-energy CRE, which could conclusively point towards one (or more than one) nearby mature pulsar as the origin of high-energy CRE, and (iii) deepen our understanding of pulsars via gamma-ray observations, and via the discovery of new gamma-ray pulsars, potentially extremely relevant as high-energy CRE sources. Last but not least, Fermi measurements of the spectrum and angular distribution of the diffuse gamma-ray emission of the Galaxy will also shed light on the nature and spatial distribution of CRE sources.

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