

Possible Interpretations of the High Energy Cosmic Ray Electron Spectrum measured with the Fermi Space Telescope

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Abstract. The Fermi Large Area Telescope has provided the measurement of the high energy (20 GeV to 1 TeV) cosmic ray electrons and positrons spectrum with unprecedented accuracy. This measurement represents a unique probe for studying the origin and diffusive propagation of cosmic rays as well as for looking for possible evidences of Dark Matter. In this contribution we focus mainly on astrophysical sources of cosmic ray electrons and positrons which include the standard primary and secondary diffuse galactic contribution, as well as nearby point-sources which are expected to contribute more significantly to higher energies. In this framework, we discuss possible interpretations of Fermi results in relation with other recent experimental data on energetic electrons and positrons (specifically the most recent ones reported by PAMELA, ATIC, PPB-BETS and H.E.S.S.).

Keywords: Cosmic ray electrons, Fermi Gamma Ray Telescope

I. INTRODUCTION

Prior to 2008, the high energy electron spectrum was measured by balloon-born experiments [1] and by a single space mission AMS-01 [2]. Those data are compatible with a featureless power law spectrum within their errors. This is in agreement with theoretical predictions (for a recent review see [3]) assuming: i) that the source term of CR electrons is treated as a time-independent and smooth function of the position in the Galaxy, and the energy dependence is assumed to be a power law; ii) that the propagation is described by a diffusion-loss equation whose effect is to steepen the spectral slope respect to the injection. Possible deviations from a simple power law spectrum may, however, be expected above several hundred GeV as a consequence of synchrotron radiation and Inverse Compton (IC) energy losses which, at those high energies, limit the electron propagation length to a distance comparable to the mean distance between astrophysical sources [4], [5] or because the possible presence of exotic sources.

Few months ago, the ATIC balloon experiment [6] found a prominent spectral feature at around 600 GeV in the total electron spectrum. Furthermore, the H.E.S.S. [7], [8] atmospheric Cherenkov telescope reported a significant steepening of the electron plus diffuse photon spectrum above 600 GeV. 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 [9], [10]. PAMELA found that the positron fraction changes slope at around 10 GeV and begins to increase steadily up to 100 GeV. This behavior is very different from that predicted for secondary positrons produced in the collision of CR nuclides with the interstellar medium (ISM).

Recently the experimental information available on the CRE spectrum has been drastically expanded as the Fermi Collaboration has reported a high precision measurement of the electron spectrum from 20 GeV to 1 TeV performed with its Large Area Telescope (LAT) [11]. A simple power law fit of the Fermi-LAT electron energy spectrum (see Fig.1) is possible giving: $J_{e\pm} = (175.40 \pm 6.09) \left(\frac{E}{1 \text{ GeV}}\right)^{-(3.045 \pm 0.008)} \text{ GeV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ with $\chi^2 = 9.7$ (for 23 d.o.f.) where statistical and systematic (dominant) errors have been, conservatively, added in quadrature. The electron spectrum measured by Fermi-LAT reveals a hardening at around 70 GeV and a steepening above ~ 500 GeV. Although the significance of those features is low within current systematics, they suggest the presence of more components in the electron high energy spectrum. It is also worth noticing here that the hard electron spectrum observed by this experiment exacerbates the discrepancy between the predictions of standard CR theoretical models and the positron fraction excess measured, most conclusively, by PAMELA [9], [10]. This makes the exploration of some non-standard interpretations more compelling.

II. CONVENTIONAL 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 electrons 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 [12]. 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 Tab. 1 in [13] 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

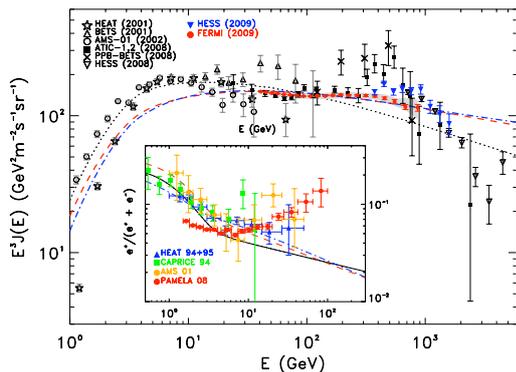


Fig. 1: Fermi-LAT CRE data [11], as well as several other experimental data sets, are compared to the $e^- + e^+$ spectrum modeled with GALPROP. The gray band represents systematic errors on the CRE spectrum measured by Fermi-LAT. The dotted (black) line correspond to the conventional model used in [14] to fit pre-Fermi data conventional model. The dashed (red) and dash-dotted (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 comparison a conventional model with $\gamma_0 = 2.54$ which was already successfully used to interpret pre-Fermi CRE data [14] and the diffuse gamma-ray emission measured by Fermi-LAT at intermediate Galactic latitudes [15].

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[2] and HEAT [16] 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 [9], [10] (see the insert in Fig. 1). While item (ii) may be interpreted as a consequence of the stochastic nature of astrophysical sources (see Sec. 2.2 in [13] and ref.s therein) the other caveats are most serious. For these reasons in the following sections we consider the possibility that an additional electron and positron primary component contribute to the observed Fermi-LAT, H.E.S.S. and PAMELA data at high energy.

III. 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. [17], [18]). 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 or the surrounding supernova remnant merge into the ISM, $10^4 - 10^5$ years after the pulsar birth. This process should be relatively fast so that *mature* pulsars can effectively be treated as burst-like sources of electrons and positrons. The possible role of these source explaining the PAMELA positron fraction anomaly [9], [10] has been discussed in several papers (see e.g. [18], [19], [20] and ref.s therein).

We compute the spectrum of electrons and positrons from each pulsar by following the approach reported in the appendix of [13]. 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. [20]) $E_{e^\pm} \simeq \eta_{e^\pm} \dot{E}_{\text{PSD}} \frac{T^2}{\tau_0}$ where \dot{E}_{PSD} is the present time spin-down luminosity determined from the observed pulsar timing, $T = P/2\dot{P}$ (where P is the pulsar period) the pulsar age, and η_{e^\pm} is the e^\pm pair conversion efficiency of the radiated electro-magnetic energy. For the characteristic luminosity decay time we assume $\tau_0 = 10^4$ years 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 [14] (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/>) [21] 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 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: $800 < E_{\text{cut}} < 1400$ 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. [22]). 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 ATNF 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 [23] has demonstrated that those pulsars are a significant fraction of the total pulsar set. We do not expect, however, that the average

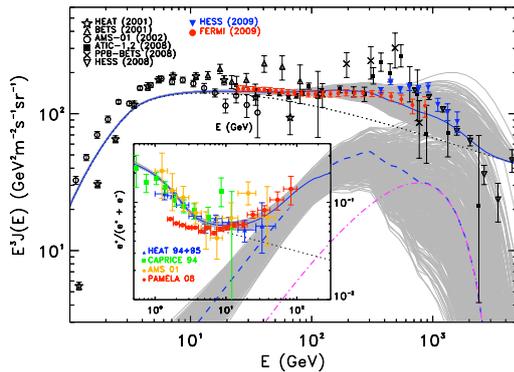


Fig. 2: The $e^- + e^+$ spectrum from pulsars plus the Galactic (GCRE) component with experimental data (dotted line). Each gray line represents the sum of all pulsars for a particular combination of pulsar parameters. The dashed (pulsars only) and solid (pulsars + GCRE component) blue lines correspond 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.

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 η_{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.

IV. 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 to 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 Sec.II, 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 Sec. II;

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* [24], and the dark matter pair-annihilates into a *light gauge boson* which can then kinematically decay only into e^\pm [25].
- 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 μ^\pm and 1/3 into τ^\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 [26], [27].
- 3) *Super-heavy dark matter models*: As pointed out in [28], 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 [29].

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 Sec.III Both the pure e^\pm model and in the lepto-philic models allow a reasonable fit to both the PAMELA and the Fermi data is possible (though the latter seems to be favored). 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 [7], [8]. The required annihilation rates, when employing a conventional dark matter density profile (see [13] for details), imply typical boost factors ranging between 20 and 100, when compared to the value $\langle\sigma v\rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{sec}$ expected for a thermally produced dark matter particle relic. The super-heavy dark matter models are significantly disfavored by Fermi-LAT and H.E.S.S. CRE data. 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 [30], [31].

V. 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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