Mem. S.A.It. Suppl. Vol. 14, 34

Memorie della
Supplementi

On possible interpretations of the high energy electron+positron spectrum measured by the Fermi-LAT

Daniele Gaggero[1,2]

[1] Dipartimento di Fisica, Università di Pisa, Largo Pontecorvo, 3, 56127 Pisa
[2] I.N.F.N., Pisa - Largo Pontecorvo, 3, 56127 Pisa
e-mail: daniele.gaggero@pi.infn.it

Abstract. The Fermi-LAT collaboration recently published a very accurate measurement of the spectrum of CR electrons+positrons from 20 GeV to 1 TeV. The reported spectrum doesn't show any prominent spectral feature, and – if systematic errors are accounted for – is consistent with a power law whose index is harder than inferred from previous experimental results. We show that the interpretation of these data, especially when combined with PAMELA results on positron-to-electron ratio, requires to reconsider the standard scenario of CR electron production and propagation in the Galaxy. After briefly discussing a simple interpretation based on slightly modified conventional CR diffusive models, we present two scenarios that consider additional sources of e^-/e^+ pairs: nearby pulsars and particle Dark Matter annihilation. We find that several combinations of parameters involving both pulsar and DM models give a satisfactory fit of all data sets. We also briefly discuss the possibility of discriminating between those two classes of sources by looking for a possible anisotropy in the CRE flux.

Key words. cosmic rays – electrons – positrons – Fermi-LAT – pulsars – dark matter

1. Introduction

Measuring the spectrum of Cosmic Ray electrons (CRE) (unless explicitly stated we define electrons to be $e^- + e^+$) with high precision and over a wide energy range is important to constrain theoretical models of production and propagation of CRs and to reveal signatures of new physics. Before 2008, the high energy electron spectrum was measured by balloon experiments and by a single space mission, AMS-01 (Aguillar et al. 2002): all data were compatible – within their uncertainties – with a featureless power-law spectrum. The situation changed in 2008, when two experiments found hints of a possible deviation from the standard picture: ATIC (Chang et al. 2008) reported a prominent spectral feature at around 600 GeV in the electron spectrum, and PAMELA (Adriani et al. 2008) found that the positron fraction changes slope at around 10 GeV and begins to increase up to ~ 100 GeV, a very different trend from that predicted for secondary positrons produced in the collision of CR nuclides with the interstellar medium (ISM). These new data suggested the pres-

Send offprint requests to: Daniele Gaggero. This analysis is based on the paper Grasso et al. 2009 ence of an additional component of electrons and positrons, either of astrophysical or exotic nature: see Grasso et al. 2009 and references therein. Very recently the experimental information available on the CRE spectrum was dramatically expanded as the Fermi-LAT Collaboration measured with high accuracy the electron spectrum from 20 GeV to 1 TeV (Abdo et al. 2009). This spectrum, if one conservatively accounts for systematic uncertainties, is compatible with a single featureless power-law of index 3.045 ± 0.008 (Grasso et al. 2009), harder than what inferred from pre-Fermi data. A closer inspection reveals a hardening at $\sim$ 70 GeV and a steepening above $\sim$ 500 GeV: these features are interesting if one tries to combine this spectrum with high-energy HESS measurements (Aharonian et al. 2008) and PAMELA data for a complete interpretation.

2. Interpreting Fermi data with a large-scale Galactic CRE component

As we showed in Grasso et al. 2009, we were able to fit Fermi-LAT data alone within the standard picture of production and propagation of CREs which is implemented in the `GALPROP`[1] numerical package, with a slight change in the source injection index, from 2.54 (the conventional value that was used to fit pre-Fermi data) to 2.42. We also provided an alternative model which doesn't include reacceleration, and we could fit the data with an index of 2.33. In both cases the normalization of the diffusion coefficient and its dependence upon energy are fixed by the requirement that the model reproduces boron-over-carbon ratio (see e.g. Strong et al. 2004 for details): in particular the values we used for δ[2] are 0.33 in the reacceleration case (as in pre-Fermi conventional models) and 0.6 in the plain diffusion case. This simple interpretation has three problems: 1) the fit gets worse at lower energies, but this discrepancy can be explained if one considers the fact that Fermi spectrum, upon which the normalization of the model is chosen, can undergo a rigid shift due to uncertainty in energy scale 2) these models are not compatible with high-energy HESS data, but this is explained considering the discrete nature of sources and the fact that at high energy CR visibility is reduced to less than 1 kpc due to energy losses 3) these models are in tension with PAMELA data, since all standard scenarios – in which positrons are secondary – lead to a decreasing positron-to-electron ratio. This is the strongest argument against this kind of interpretation, which led us to consider an extra source of $e^{\pm}$ pairs.

[1] a description of GALPROP code can be found at http://galprop.stanford.edu

[2] δ is the slope of the power-law that describes the dependence of diffusion coefficient upon energy

3. Pulsar interpretation

The first scenario that invokes an extra-component is based on conventional astrophysical objects. Pulsars are natural candidates in this context, since they are undisputed sources of relativistic electrons, believed to be produced in the magnetosphere and subsequently possibly reaccelerated by the pulsar winds or in the supernova remnant shocks. In particular, we are interested in *mature* pulsars, because electron-positron pairs accelerated in the Pulsar Wind Nebula should be confined in the nebula itself until it merges into the ISM, 10^4 - 10^5 years after its formation. At energies between $\sim$ 100 GeV and $\sim$ 1 TeV the electron flux reaching the Earth may therefore be the combination of a diffuse galactic component produced by supernova remnants and the local contribution of a few nearby pulsars, with the latter expected to contribute more and more significantly as the energy increases. In order to account for this possibility, here we sum the electron spectrum from observed nearby pulsars to the CRE component computed with `GALPROP`. The spectrum of the pulsars is computed solving analitically the same diffusion-loss equation which is implemented in `GALPROP`, with the same choice of diffusion parameters, so the two components are compatible; instead, the background we use is the same conventional model which was used in pre-Fermi era, rescaled by a factor $\approx$ 0.95.

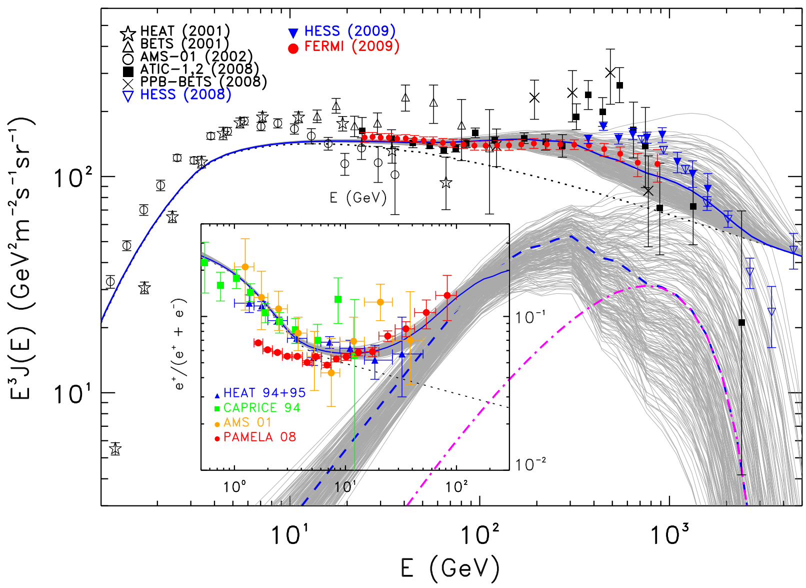

Fig. 1. Comparison of the electron spectrum and the positron fraction predicted in the pulsar scenario with experimental data. Each grey line corresponds to a different realization of the method described in the text, with different choices of parameters for each pulsar. The blue dashed (pulsars only) and blue solid lines (pulsars + galactic diffuse component) correspond to a representative choice among that set of possible realizations. The purple dot-dashed line represents the contribution of Monogem pulsar.

We modeled the emission from a pulsar as a power-law with exponential cutoff. So, the emission of a pulsar of age T situated at distance d is characterized by four almost free parameters: the slope of injection curve Γ, the cutoff energy $E_{\rm cut}$, the efficiency η and the delay Δt of $e^- + e^+$ pair emission with respect to pulsar birth. Since these parameters are very loosely constrained by independent observations, we randomly varied them in the reasonable ranges $800 < E_{\rm cut} < 1400$ GeV, $10 < \eta < 30$ % and $5 < (\Delta t/10^4 \text{ yr}) < 10$ and $1.5 < \Gamma < 2.0$. The results are shown in figure 1, in which we considered all known pulsars older than 50 kyr in the ATNF radio pulsar catalogue within a distance of 3 kpc, and summed their contributions, each with a randomly varied set of parameters. It is evident that, under reasonable assumptions, Fermi-LAT and HESS data on the electron spectrum and PAMELA data are consistent with this scenario.

4. Dark matter interpretation

A DM interpretation of Fermi-LAT and of the PAMELA data is still an open possibility. Nevertheless we note that this kind of interpretation seems disfavored because: 1) astrophysical sources (pulsars, supernova remnants) can account for the observed spectral features, as well as for the positron ratio measurements 2) DM models generally produce antiprotons. Since no excess in the $\bar{p}/p$ ratio is reported by PAMELA, only models with some mechanism that suppresses antiproton production must be considered 3) the annihilation rate required to explain the excess of electrons and positrons is roughly two order of magnitude larger than the predicted one, assuming DM is weakly in-

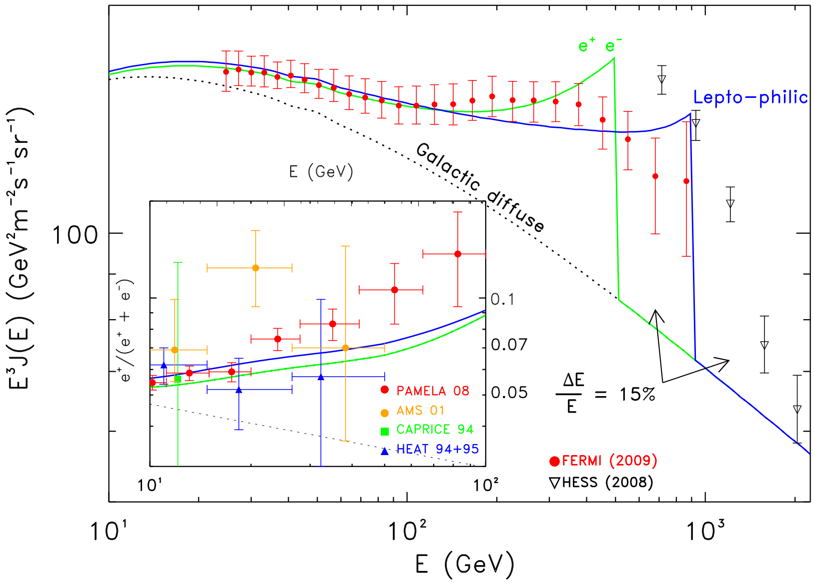

Fig. 2. CRE spectrum and positron ratio from DM models described in the text, compared to current measurements. The blue line corresponds to the leptophilic model (galactic diffuse + DM source) and the green line corresponds to the pure $e^{\pm}$ model.

teracting, and that it was produced in the early Universe via an ordinary freeze-out process. In spite of the above considerations, our aim in this section is to illustrate that with particular choices of the mass and annihilation rate of DM particles, all data sets are compatible with a DM scenario; for a more detailed discussion on the constraints that new Fermi-LAT data set on the parameter space, see Grasso et al. 2009. We show in fig. 2 the results we obtained with two classes of models in which $\bar{p}$ production is suppressed: 1) *pure* $e^{\pm}$ *models*: DM pair annihilation always yields a pair of monochromatic $e^{\pm}$; we chose a mass of 500 GeV and $\langle\sigma v\rangle = 1.2\times10^{-24}$ 2) *lepto-philic models*: we assume equal pair-annihilation branching ratio into each charged lepton species: 1/3 into $e^{\pm}$, 1/3 into $\mu^{\pm}$ and 1/3 into $\tau^{\pm}$; we chose a mass of 900 GeV and $\langle\sigma v\rangle = 5.5\times10^{-24}$. The latter is clearly favoured by Fermi-LAT + HESS data. We point out that a possible way to distinguish between this scenario and the pulsar interpretation is the anisotropy measurement of the high energy CRE flux: in the DM scenario a possible anisotropy is expected pointing in the direction of the Galactic Center or of a local DM clump, while in the pulsar model we expect a $\sim$ 1% anisotropy at $\sim$ 1 TeV towards Monogem, the most luminous nearby mature pulsar.

5. Conclusions

We discuss some possible interpretations for the cosmic ray electron spectrum measured by Fermi-LAT. The measured CRE flux is significantly harder than previously believed and does not show any sharp feature in the multi-hundred GeV range, although there are hints of an extra-component between 100 and 1000 GeV. We discussed the case of a single large-scale diffuse Galactic (GCRE) component, and a two-component scenario which adds to the GCRE flux a primary component produced by either mature pulsars or DM annihilation. The first interpretation is in sharp tension with the PAMELA data on the positron fraction and also with pre-Fermi experimental data on electron flux below 10 GeV. Taking into account mature pulsars as additional sources of high-energy CRE, we showed that both the PAMELA positron excess and the Fermi-LAT CRE data are naturally explained under reasonable assumptions. We also considered another possible primary source of high-energy CRE: the annihilation or decay of dark matter in the Galactic halo, showing that a DM particle annihilating in leptonic channels, with a mass close to 1 TeV, is compatible with both the e^+ excess reported by PAMELA and with the CRE spectrum measured by Fermi-LAT.

References

Abdo A.A. et al. [Fermi collaboration] 2009, Phys. Rev. Lett., 102

Adriani O. et al. [PAMELA Collaboration] 2009, Nature, 458, 607

Aguilar M. et al. [AMS-01 Collaboration] 2002, Physics Reports, 366, 331

Aharonian F. et al. [H.E.S.S. Collaboration] 2008, Phys. Rev. Lett., 101

Chang J. et al. [ATIC Collaboration] 2008, Nature, 456, 362

Grasso D. et al. 2009, Astropart. Phys., accepted, [astro-ph/0905.0636]

Strong A.W., Moskalenko I.V. & Reimer O., 2004, ApJ, 613, 962.