

THE COSMIC RAY LEPTONS PUZZLE

Brun, P.¹, Bertone, G.², Cirelli, M.³ and Moulin, E.¹

Abstract. Recent measurements of cosmic ray electrons and positrons by PAMELA, ATIC, Fermi and HESS have revealed interesting excesses and features in the GeV-TeV range. Many possible explanations have been suggested, invoking one or more nearby primary sources such as pulsars and supernova remnants, or dark matter. Based on the output of the TANGO in PARIS –Testing Astroparticle with the New GeV/TeV Observations in Positrons And electRons : Identifying the Sources– workshop held in Paris in May 2009, we review here the latest experimental results and we discuss some virtues and drawbacks of the many theoretical interpretations proposed so far.

1 Introduction

Cosmic ray leptons (electrons and positrons) are very interesting for the main reason that they probe our local Galactic environment as they propagate on a few kpc only. Their energy spectrum can encode lots of information about the source(s). In fact, because they lose energy very efficiently as they propagate, there are strong correlations between the spectral features and the distance to the source(s). For those reasons, and because the matter/antimatter ratio is higher than for other species such as protons, the leptonic channel has always been thought to be a good way to search for dark matter annihilation debris. In this paper we briefly review recent measurements of cosmic ray leptons as well as some possible interpretations. Note that this brief review cannot be all comprehensive by itself, for more details and discussions we invite the reader to consult the website of the TANGO in PARIS workshop.

2 The measurements

High energy leptons produce showers when passing through matter, they are observed with the help of calorimeters. For cosmic ray studies detectors can be magnetic spectrometers in which case they perform charge identification and separate electrons from positrons, or simple calorimeters in which case they measure the $e^- + e^+$ sum. Recent measurements are displayed in Fig. 1. PAMELA measured the positron fraction ($e^+/(e^- + e^+)$) between 1 GeV and ~ 100 GeV (R. Sparvoli). An unambiguous rise of the fraction is observed above 10 GeV, as some previous experiments found some hints for. Other results are obtained without charge identification by the balloon experiment ATIC (J. Isbert), the Fermi satellite (J. Bregeon) and the ground-based HESS Čerenkov telescopes (K. Egberts). Data points are shown on the right panel of Fig. 1. The ATIC detector has 22 radiation lengths and a few % energy resolution, the ATIC collaboration claims the observation of a sharp peaked structure in the $e^- + e^+$ spectrum at ~ 600 GeV. The same measurement as performed by Fermi (8.5 radiation length, $\sim 10\%$ energy resolution) does not show such a prominent structure, but rather a smooth bump. The interesting region is at the edge of the HESS sensitivity, which observes a break in the spectrum. However, due to $\sim 15\%$ energy scale uncertainty, HESS data points hardly constraint the precise shape of the excess. At the moment, the data seem inconsistent. Note however that large systematics (not displayed in Fig. 1) are present. Up to now it is still unclear which spectrum is closer to reality. However, whatever the real spectrum, these data probably indicate the presence of a nearby yet undetermined cosmic ray leptons source, as exposed below.

¹ CEA, Irfu, Service de Physique des Particules, Centre de Saclay, F-91191 Gif sur Yvette, France

² Institut d'Astrophysique de Paris, France. UMR7095-CNRS UPMC, 98bis Boulevard Arago, 75014 Paris, France

³ Institut de Physique Théorique, CNRS URA 2306 & CEA/Saclay, F-91191 Gif-sur-Yvette, France

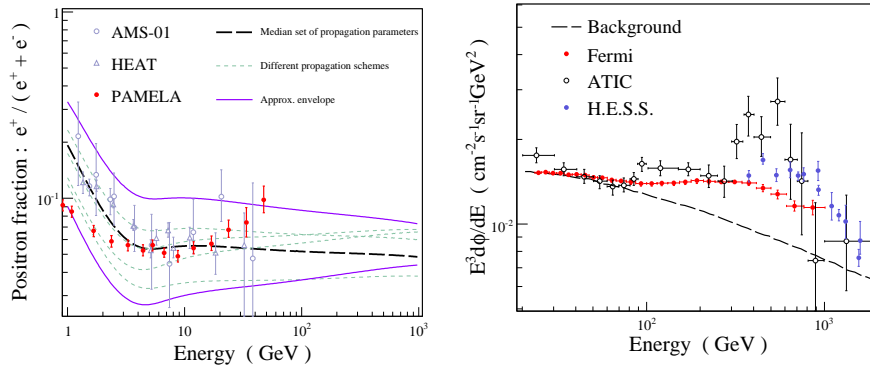


Fig. 1. Cosmic ray positron fraction (left) and electrons+positrons fluxes (right).

3 Models for cosmic ray transport

In the energy range which is considered here (GeV to TeV), it is thought that the bulk of cosmic rays comes from supernovae and their remnants. These sources are located in the Galactic disk, which is a few tenths of parsecs thick and whose radius is ~ 30 kpc. Once produced and accelerated in the sources, they diffuse inside a flat ~ 10 kpc cylinder in which they are deflected by the turbulences of magnetic fields. In addition, they can loose energy and get affected by the convective wind blowing from the disk outwards. The cosmic rays that are directly produced in the sources are called primaries. Some species found in cosmic rays (such as positrons, antiprotons, boron, etc.) do not originate from stars. These species are produced during the transport of primaries, by spallation reactions onto the interstellar medium.

Two approaches are used to compute cosmic ray fluxes at the Earth in order to compare with the measurements: semi-analytical (D. Maurin) and fully numerical (A. Strong). In the first case, mean values are used for the source properties (spatial distribution, intrinsic spectrum, etc.) and propagation parameters (diffusion coefficient, energy losses efficiencies, etc.), and simple boundary conditions are employed. The main advantage of this method is that it is much faster, thus allowing large scans of the propagation parameter space. This essential property permits to compute theoretical uncertainties on the flux as well as on any quantity derived from these parameters. In this framework, it is also easier to perform studies on the spatial origin of sources and local effects. The numerical approach is used in the Galprop code, which is a publicly available tool. In this framework, all type of data is used in a self-consistent way, including 3D gas model, cosmic ray sources, radiation fields, Galactic magnetic field model, etc. This allows in particular the computation of γ -ray diffuse fluxes, and the production of synchrotron skymaps, which the semi-analytical method still does not do.

This brief description of the computational tools is essential, because when a claim for a excess in some channel is made, those are the methods which are used to determine the expected background. An important point is that whatever the method to estimate the local cosmic ray lepton fluxes, conventional computations cannot account for the observed features. In other words, there is no allowed set of diffusion parameters which reproduces leptonic data with secondaries only. Indeed, these estimates lead to the mean secondary flux one can expect at the Earth location, but it is also shown that there should be large fluctuations in the spatial density of cosmic rays. This depends whether or not a primary source lies in the Earth neighborhood. Ordinary sources such as supernova remnants carry the same baryon number as the whole Universe so that antiparticles should be subdominant. The fact that the positron fraction is $\sim 10\%$ might be already betraying their nature as secondary species; as most primaries are protons, charge conservation leads to a higher yield of positive charges within secondaries. As electrons and positrons only propagate on short distances of order 1 kpc, the observation of a rise of the positron fraction and a bump in the inclusive spectrum leads to the conclusion that there is a nearby source of high energy e^+/e^- pairs. In the following different possibilities for such a nearby source are reviewed, as well as possible constraints from multi-wavelength and other channels analyses.

4 Interpretations of the data

4.1 Conventional sources

As explained above, it is suspected that a nearby source of electrons and positrons significantly contributes to the measured flux. We first investigate standard sources which are known to exist, more exotic ideas are discussed in Sec. 4.2. As for conventional sources, one can mention two types : electromagnetic sources and non-electromagnetic ones. In the first case, pairs are produced via purely electromagnetic processes. These sources can be *e.g.* pulsars or γ -ray binaries. For these sources, counterparts in γ rays are expected. The second class of sources imply hadronic processes as well, it can be any type of astrophysical shock, like in supernova remnants. In that case, counterparts are expected in γ -rays and possibly in the antiproton channel as well.

Pulsars are good candidates for being the nearby source responsible for the excesses. They are rotating and strongly magnetized neutron star, within which e^\pm pairs can be created in magnetic fields or by high energy photons collisions (B. Rudak). TeV-level leptons can be produced and accelerated in the environment of the neutron star and released in the interstellar medium provided the matter is diluted enough. For that last reason, mature pulsars such as Geminga, Loop I, Monogem (and others) are excellent candidates. All the data can be well fitted by adding pulsars to the conventional flux (I. Buesching, see Fig. 2). However, there is yet no obvious unique candidate as there are still free parameters in the models. In its first year of data taking, the Fermi satellite discovered plenty new pulsars showing that these objects seem to be ubiquitous in our Galactic environment. Unfortunately, a clear counterpart in γ -ray is not expected as the time scales for photons and charged particles are very different at all levels of the models (production, propagation).

Concerning supernova remnants, another possibility would be that secondary particles directly produced at the source had not been previously accounted for properly. In the standard picture, remnant material from the exploding star constitutes a shock in which particles are accelerated. It is now suggested that secondary particles produced in the shock itself could significantly increase the escaping positron fraction (P. Blasi). Decent fits of the data are obtained within this scenario, which turns out to be falsifiable. This model predicts a rise of the antiproton to proton ratio above 100 GeV. The PAMELA satellite has now precise results up to ~ 100 GeV and it is foreseen to measure higher energy antiprotons. Therefore it will be possible to test this scenario in the near future.

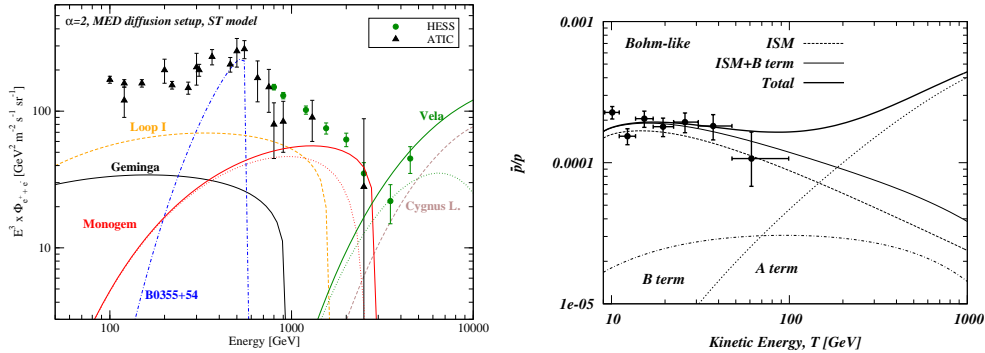


Fig. 2. Fit of the electron data with pulsars (plot from S. Profumo) and \bar{p} predictions in case of secondary production within a supernovae remnant (P. Blasi).

4.2 Exotic ideas

Although it is definitely possible to reproduce the leptonic data with conventional sources, an extensively studied possibility would be that the features have a dark matter related origin. Observational data show that our Galaxy stars are dipped in a spherical dark halo whose extension is 10 times larger than the luminous disc. The dark matter appears to be non baryonic and could consist of massive yet undiscovered particles. It is believed that these particles were created in the early Universe and now haunt Galaxies. These particles must have very small interactions with conventional matter. It is possible however that they could decay or annihilate (A. Ibarra, M. Cirelli). The annihilation or decay product should carry no baryonic charge, thus producing

standard particles and antiparticles in a 1:1 ratio. These process happen in the Galactic halo –possibly in the Earth neighborhood–, and the produced particles then diffuse just like conventionally produced cosmic rays, thus enlarging the antiparticle ratio.

Annihilating dark matter is particularly studied as the involved orders of magnitude nicely converge towards a canonical picture. Dark matter particles appear in Standard Model extensions which are often related to the breaking of the electroweak symmetry. In this framework, Weakly Interacting Massive Particles (WIMPs) have electroweak scale mass which is the same order of magnitude as the cosmic leptons features. Primordial self annihilations regulate the cosmological density, which defines a natural value for the annihilation cross section. As this value is close to the one inferred from electroweak scale interactions, this fact gives credit to the WIMP model. Unfortunately, when computing the related exotic cosmic ray production rate, canonical values gives lepton fluxes that are too low by 2-3 orders of magnitude. One needs then to invoke some mechanism for the enhancement of the annihilation rate. A possibility is an enhancements due to dense dark matter substructure, but this seems somehow unlikely (J. Lavalle). This can be achieved by assuming *e.g.* a non thermal production in the early Universe (then the annihilation cross section is not constrained from that). A more elegant solution appears for TeV scale WIMPs with the help of the Sommerfeld effect. This happens when masses and couplings have specific values which makes the annihilation cross section increase when parameters lead to WIMPs almost-bound states (J. Hisano). In that case, the colder the dark matter particles, the higher the annihilation cross section. It is essential though to compare exotic cosmic ray leptons with other messengers. For instance, PAMELA precisely measured the antiproton fluxes up to ~ 100 GeV. Generic dark matter particles annihilations should produce antiprotons as well, so that antiproton measurement can constrain the production rate for exotic cosmic rays. It is shown that the enhancement factor for a conventional WIMP cannot exceed a factor of ~ 10 not to overproduce antiprotons (F. Donato). To save the WIMP interpretation, it is therefore required to assume that hadronic annihilation channels are suppressed, leaving open only leptonic ones. This is the so-called leptophilic dark matter, for which a case can be made from the model-building point of view (either with supersymmetry (N. Fornengo) or within new classes of models (Y. Nomura)).

Links with other wavelength are also under investigation (how the electrons/positrons excesses can be linked to the 511 keV emission at the Galactic center (P. Jean) or the WMAP haze (G. Dobler)). The most conclusive results come from radio and γ ray data from the Galactic center and dwarf galaxies. Indeed if these leptons are from dark matter particle collisions, they should be produced in large quantity in other locations. For example, corresponding leptons should be produced at the Galactic center and generate radio waves while interacting with the magnetic field, which are above current observations. In general, even leptophilic dark matter is in conflict with other messengers/wavelength observations, at least within most straightforward models for dark matter distributions and magnetic fields.

5 Outlook

Most likely the lepton excesses observed by PAMELA, ATIC, Fermi and HESS are not caused by conventional secondary cosmic rays, meaning that a nearby source significantly contributes to the local flux. The main classes of candidate are astrophysical (*e.g.* a nearby pulsar or supernova remnant) or more exotic. The first case seems favored as one has to invoke non conventional scenarios for dark matter in order to avoid constraints from different observables. It is however very exciting to notice that we might be witnessing the direct effects of a TeV cosmic ray source for the first time. Further data analyses of current experiments will certainly provide important information, like whether one can detect a small anisotropy and its direction. Eventually, future experiments, both on the ground (K. Mannheim) or balloon borne and spatial detectors (L. Derome) will certainly offer the opportunity to have a deeper look into this problem.

We would like to warmly thank all the TANGO in PARIS speakers, as well as the members of the organizing committee : F. Aharonian, O. de Jager, J-F. Glicenstein, F. Iocco, R. Mohayaee, L. Pieri, P. Serpico and J. Silk. We acknowledge the Institut d'Astrophysique de Paris, ANR, IPhT/ CEA Saclay, Irfu/CEA Saclay, GdR Terascale and GdR PCHE for their support.

References

All citations refer to the TANGO in PARIS talk (and references therein) by the quoted author. Slides and videos of the talks are available at:
<http://irfu.cea.fr/Meetings/TANGOinPARIS>