The status of the $e^{\pm}$ cosmic-ray anomaly

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Abstract. Via a Bayesian likelihood analysis using 219 cosmic ray data points we extract the anomalous part of the cosmic $e^{\pm}$ flux. First we show that a serious tension exists between the $e^{\pm}$ fluxes and the rest of the data. Interpreting this tension as effect of an anomalous component on the $e^{\pm}$ related data, we then infer the values of selected cosmic ray propagation parameters excluding the anomalous data sample from the analysis. Based on these values we calculate background predictions with theoretical uncertainties for PAMELA and Fermi-LAT. We find a statistically significant deviation between the Fermi-LAT $e^{-} + e^{+}$ data and the predicted background even when (systematic) uncertainties are taken into account. Identifying this deviation as an anomalous $e^{\pm}$ contribution, we make an attempt to distinguish between various sources that may be responsible for the anomalous $e^{\pm}$ flux.

1. Introduction
Cosmic ray observations provided significant and puzzling deviations from theoretical predictions over the last decades. Experiments such as TS [1], AMS [2], CAPRICE [3], MASS [4], and HEAT [5, 6] established a hint of an excess of high energy electrons and/or positrons. Measurements of the PAMELA satellite confirmed these results by finding an excess over the theoretical predictions in the $e^{-}/(e^{-} + e^{+})$ flux for $E > 10$ GeV [7]. The PAMELA data seem to deviate from the theoretical predictions even when theoretical and experimental uncertainties are taken into account [8]. An excess in the $e^{-} + e^{+}$ flux was also found by AMS [9], PPB-BETS [10], and HESS [11, 12]. Recently the Fermi-LAT satellite confirmed the $e^{-} + e^{+}$ excess above 100 GeV [13]. The deviation between the Fermi-LAT data and the theoretical $e^{-} + e^{+}$ prediction is significant. This deviation was reinforced by PAMELA which found the $e^{-}$ flux to be consistent with the Fermi-LAT data.

Many attempts were to explain the deviation between the data and theory. New physics was invoked ranging from modification of the cosmic ray propagation, through supernova remnants, to dark matter annihilation. Ref. [14] summarizes these speculations. Whether the $e^{\pm}$ anomaly exists depends on the the cosmic ray background prediction. The theoretical prediction is challenging because of the lack of precise knowledge of the cosmic ray sources, and because the cosmic ray propagation model has numerous free parameters, such as convection velocities, spatial diffusion coefficients and momentum loss rates.

Motivated by traces of possible new physics in the Fermi-LAT data, we attempt to determine the size of the anomalous component in the $e^{\pm}$ flux. Our method involves the following steps. First we find the parameters of the cosmic ray propagation that influence the $e^{\pm}$ flux measured by Fermi-LAT and PAMELA the most. Then we subject the cosmic ray data, other than the
Fermi-LAT and PAMELA $e^\pm$ measurements to a Bayesian likelihood analysis, to determine the preferred values and the 68 % (1-σ) credibility regions of the relevant propagation parameters. Based on the central values and 1-σ credibility regions of these propagation parameters we then predict the background flux, with uncertainties, for Fermi-LAT and PAMELA. Finally, we extract the anomalous part of the spectrum by subtracting the background prediction from the Fermi-LAT and PAMELA measurement.

2. Theory of cosmic ray propagation

Galactic cosmic ray propagation is modeled by the diffusion-convection theory [15]. This model assumes the homogeneous propagation of charged particles within the Galactic disk and it also includes energy loss effects. The phase-space density $\psi_a(\vec{r},p,t)$ of a cosmic ray species, labelled by $a$, at a Galactic radius of $\vec{r}$ can be calculated solving the transport equation which has the general form [16]

$$\frac{\partial \psi_a(\vec{r},p,t)}{\partial t} = Q_a(\vec{r},p,t) + \nabla \cdot (D_{xx} \nabla \psi_a - \vec{V} \psi_a) - \frac{1}{\tau_f} \psi_a$$

$$+ \frac{\partial}{\partial p} \left( p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_a \right) - \frac{\partial}{\partial p} \left( \dot{p} \psi_a - \frac{p}{3} (\nabla \cdot \vec{V}) \psi_a \right).$$

(1)

Here $q(\vec{r},p,t)$ is the source term of primary and secondary cosmic ray contributions. The spatial diffusion coefficient $D_{xx}$ has the form

$$D_{xx} = D_{0xx} \beta \left( \frac{R}{\text{GeV}} \right) ^\delta ,$$

(2)

where $\beta = v/c$, and $R = pc/eZ$ is the (magnetic) rigidity of the particles which describes a particle’s resistance to deflection by a magnetic field. Above $Z$ is the effective nuclear charge of the particle, $e$ is its charge, $p$ is its momentum, $v$ is its velocity, and $c$ is the speed of light. The exponent $\delta$ indicates the power law dependence of the spatial diffusion coefficient $D_{xx}$.

Diffusion in momentum space (diffusive re-acceleration) is described by the coefficient $D_{pp}$

$$D_{pp}D_{xx} = \frac{4p^2 v_A^2}{3\delta(4 - \delta^2)(4 - \delta)w}.$$  

(3)

Here $v_A$ is the Alfvén speed, the parameter $w$ characterises the level of hydromagnetic turbulence experienced by the cosmic rays in the interstellar medium [17]. In Eq.(1), $\vec{V}$ is the convection velocity and the parameter $\tau_f$ is the time-scale of the fragmentation loss, and $\tau_r$ is the radioactive decay time-scale.

The GalProp numerical package solves the propagation equation numerically for $Z \geq 1$ nuclei, as well as for electrons and positrons on a two dimensional spatial grid with cylindrical symmetry in the Galaxy [16]. The input parameter file for GalProp has a number of free parameters which are available for the author to define. These can be classified into a number of subsets: the diffusion of cosmic ray, the primary cosmic ray sources and radiative energy losses of these primary cosmic rays. The diffusion parameters, defined above, are:

$$D_{0xx}, \delta, L, v_A, \partial \vec{V}/\partial z.$$  

(4)

Parameters that are the most relevant for the primary cosmic ray sources are:

$$R_{i,\text{ref}}^- e^- , \gamma_1^- , \gamma_2^- , R_{\text{ref}}^\text{nucleus} , \gamma_1^\text{nucleus} , \gamma_2^\text{nucleus}.$$  

(5)

Here $\gamma_1^-$ and $\gamma_2^-$ are primary source electron injection indices. They specifying the steepness of the electron injection spectrum, $dq(p)/dp \propto p^{\gamma_i^-}$, below ($i = 1$) and above ($i = 2$) of a reference rigidity ($R_{i,\text{ref}}^-$). There are injection indices for nuclei defined by $\gamma_1^\text{nucleus}$ and $\gamma_2^\text{nucleus}$ below and above $R_{\text{ref}}^\text{nucleus}$. For further details we refer the reader to [16].
3. Parameter space, uncertainties and experimental input

We tested the robustness of the $e^{\pm}$ flux against the variation of nearly all propagation parameters individually. We found that the $e^{\pm}$ flux is mostly sensitive to the following parameters:

$$P = \{\gamma_{1e}, \gamma_{2nucleus}, \delta_1, \delta_2, D_{0xx}\}. \quad (6)$$

Here $\delta_1$ and $\delta_2$ are spatial diffusion coefficients below and above a reference rigidity $\rho_0$, $\gamma_{1e}$ and $\gamma_{2nucleus}$ are the primary electron and nucleus injection indices, and $D_{0xx}$ determines the normalization of the spatial diffusion coefficient.

Our calculations confirmed the findings of the study by [18] that the $e^{\pm}$ flux is sensitive to the value of the Galactic plane height $L$. Indeed [17] have shown that there is a connection between $L$ and $D_{0xx}$:

$$D_{0xx} = \frac{2c(1-\delta)}{3\pi w_0(\delta+2)}L^{1-\delta}. \quad (7)$$

Thus, varying the cylinder height is the same as the redefinition of $D_{0xx}$ [19]. Realizing this we use $D_{0xx}$ as free parameter and fix $L$ to 4 kpc.

We treat the normalizations of the $e^{-}$, $e^{+}$, $\bar{p}/p$, $B/C$, $(SC+Ti+V)/Fe$ and $Be-10/Be-9$ fluxes as nuisances parameters.

$$P_{nuisance} = \{\Phi_{0e^-}, \Phi_{0e^+}, \Phi_{0\bar{p}/p}, \Phi_{0B/C}, \Phi_{0(SC+Ti+V)/Fe}, \Phi_{0Be-10/Be-9}\}. \quad (8)$$

When evaluating uncertainties, following [20], we ignore theory uncertainties and combine statistical and systematic experimental uncertainties as

$$\sigma_i^2 = \sigma_{i,\text{statistical}}^2 + \sigma_{i,\text{systematic}}^2. \quad (9)$$

This can be done for Fermi-LAT and the latest PAMELA $e^-$ flux. Unfortunately, systematic uncertainties are not available for the rest of the cosmic ray measurements. When this is the case, to parametrize the systematics, we rescale the statistical uncertainty to define $\sigma_i$

$$\sigma_i^2 = \sigma_{i,\text{statistical}}^2/\tau_i. \quad (10)$$

For simplicity, we use the same scale factor for all data points where systematic uncertainty is not available. To remain consistent with Ref. [20], we set this common scale factor to a value that they use ($\tau_i = 0.2$). We checked that our conclusions are robust against this choice. Further details about our Bayesian parameter inference can be found in [21].

We included 219 of the most recent experimental data points in our statistical analysis. These contained 114 $e^{\pm}$ related, and 105 $\bar{p}/p$, $B/C$, $(SC+Ti+V)/Fe$ and $Be-10/Be-9$ cosmic ray flux measurements. These data are summarized in Table 1.

4. The size of the $e^{\pm}$ anomaly

We begin by investigating whether the present cosmic ray data justify the existence of an anomaly in the $e^{\pm}$ spectrum. To this end we divide the cosmic ray data into two groups: 114 measurements containing observations of $e^{\pm}$ fluxes (AMS, Fermi, HESS, and PAMELA) and the rest of 105 data points ($\bar{p}/p$, $B/C$, $(SC+Ti+V)/Fe$, $Be-10/Be-9$). We perform a Bayesian analysis independently on these two sets of data extracting the preferred values of the propagation parameters.

Fig. 1 shows that the two subsets of cosmic ray data are not consistent with the sources implemented in GalProp, or with the cosmic ray propagation model altogether. Our interpretation of this tension between the $e^{\pm}$ data and the rest of the cosmic ray fluxes is the
Table 1. Cosmic ray experiments and their energy ranges over which we have chosen the data points for our analysis. We split the data into two groups: $e^\pm$ flux related (first five lines in the table), and the rest. We do two Bayesian analyses in parallel to show the significant tension between the two data sets.

| Measured flux | Experiment              | Energy (GeV) | Data points |
|---------------|-------------------------|--------------|-------------|
| $e^+ + e^-$   | AMS [9]                 | 0.60 - 0.91  | 3           |
|               | Fermi-LAT [13]          | 7.05 - 886   | 47          |
|               | HESS [11, 12]           | 918 - 3480   | 9           |
| $e^+/(e^+ + e^-)$ | PAMELA [22]        | 1.65 - 82.40 | 16          |
| $e^-$         | PAMELA [23]             | 1.11 - 491.4 | 39          |
| $\bar{p}/p$   | PAMELA [24]             | 0.28 - 129   | 23          |
| B/C           | IMP8 [25]               | 0.03 - 0.11  | 7           |
|               | ISEE3 [26]              | 0.12 - 0.18  | 6           |
|               | Lezniak et al. [27]     | 0.30 - 0.50  | 2           |
|               | HEAO3 [28]              | 0.62 - 0.99  | 3           |
|               | PAMELA [29]             | 1.24 - 72.36 | 8           |
|               | CREAM [30]              | 91 - 1433    | 3           |
| (Sc+Ti+V)/Fe  | ACE [31]                | 0.14 - 35    | 20          |
|               | SANRIKU [32]            | 46 - 460     | 6           |
| Be-10/Be-9    | Wiedenbeck et al. [33]  | 0.003 - 0.029 | 3         |
|               | Garcia-Munoz et al. [34]| 0.034 - 0.034 | 1         |
|               | Wiedenbeck et al. [33]  | 0.06 - 0.06  | 1           |
| (Sc+Ti+V)/Fe  | ISOMAX98 [35]           | 0.08 - 0.08  | 1           |
|               | ACE-CRIS [36]           | 0.11 - 0.11  | 1           |
|               | ACE [37]                | 0.13 - 0.13  | 1           |
|               | AMS-02 [38]             | 0.15 - 9.03  | 15          |

following. The measurements of PAMELA and Fermi-LAT may be affected by new physics. This new physics is unaccounted for by the cosmic ray sources included in our calculation or by the propagation model.

We use the central values and credibility regions of the parameters determined using the non-$e^\pm$ related data to calculate a background prediction for the $e^\pm$ fluxes. Fig. 2 shows the measured $e^\pm$ fluxes and the calculated background. Statistical and systematic uncertainties combined in quadrature are shown for Fermi-LAT, while ($\tau = 0.2$) scaled statistical uncertainties are shown for PAMELA $e^+/(e^+ + e^-)$ as gray bands. Our background prediction is overlaid as magenta bands. The central value and the 1-$\sigma$ uncertainty of the calculated anomaly is displayed as green dashed lines and bands. As the first frame shows the Fermi-LAT measurements deviate from the predicted background both below 10 GeV and above 100 GeV.

In our interpretation the deviation is a statistically significant signal of the presence of new physics in the $e^+ + e^-$ flux. Based on the difference between the central values of the background and the data a similar conclusion can be drawn from PAMELA. Unfortunately, the large PAMELA uncertainties prevent us to claim a significant deviation. After having determined the background for the $e^\pm$ fluxes, we subtract it from the measured flux to obtain the size of the new physics signal. Results for the $e^\pm$ anomaly are also shown in Fig. 2. As expected based on the background predictions a non-vanishing anomaly can be established for the Fermi-LAT $e^+ + e^-$ flux, while no anomaly with statistical significance can be claimed for
Figure 1. Marginalized posterior probability distributions of propagation parameters listed in Eq.(6). The dashed blue curves show results with likelihood functions containing $e^\pm$ flux data while the likelihood functions for the solid red curves contain only the rest of the cosmic ray data. Shaded areas show the 68 % credibility regions. A statistically significant tension between the $e^\pm$ and the rest of the data is evident in the lower frames.

Figure 2. Electron-positron fluxes measured by Fermi-LAT and PAMELA (gray bands) with the extracted size of the $e^\pm$ anomaly (green bands). Combined statistical and systematic uncertainties are shown for Fermi-LAT and PAMELA $e^-$, while ($\tau = 0.2$) scaled statistical uncertainties are shown for PAMELA $e^+/(e^+ + e^-)$. Our background predictions (magenta bands) are also overlaid.
PAMELA due to the large uncertainties.

At this stage we can only speculate about the origin of the difference between the data and background predictions of the cosmic $e^\pm$ spectra. One possibility is that some aspect of the propagation model is insufficient for the proper description of the electron-positron fluxes arriving at Earth [39]. In this case there exists no anomaly in the data. Assuming that the propagation model satisfactorily describes physics over the Galaxy the next reasonable thing is to suspect local effects modifying the electron-positron distribution [40]. Further suspicion falls on the lack of sources included in the calculation [41].

Two major categories of possible new sources that could account for the anomaly have been proposed. The first category is standard astrophysical objects such as supernova remnants, pulsars, various objects in the Galactic centre, etc. Finally, more exotic explanations call for new astronomical and/or particle physics phenomena, such as dark matter. In Ref. [21] we compared our extracted signal to recent predictions of anomalous sources. We considered predictions from supernova remnants, nearby pulsars and dark matter annihilation. We concluded that presently uncertainties are too large and prevent us from judging the validity of these as explanations of the anomaly. With more data and more precise calculations the various suggestions of the cosmic $e^- + e^+$ anomaly can be confirmed or ruled out.

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