PROCEEDINGS OF SCIENCE

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

Katie Auchettl[*]
School of Physics, Monash University, Victoria 3800 Australia and
ARC Centre of Excellence for Particle Physics at the Tera-scale
E-mail: `Katie.Auchettl@monash.edu`

Csaba Balázs[†]
School of Physics, Monash University,
ARC Centre of Excellence for Particle Physics at the Tera-scale and
Monash Centre for Astrophysics, Victoria 3800 Australia
E-mail: `Csaba.Balazs@monash.edu`

We extract the anomalous part of the cosmic $e^{\pm}$ flux via a Bayesian likelihood analysis using 219 cosmic ray data points. First we show that serious tension exists between the $e^{\pm}$ fluxes and the rest of the data. Interpreting this tension as an effect of an anomalous component on the $e^{\pm}$ data, we infer the values of selected cosmic ray propagation parameters by excluding the $e^{\pm}$ data 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 show that increased precision is required to distinguish between various sources that may be responsible for this contribution.

36th International Conference on High Energy Physics,
July 4-11, 2012
Melbourne, Australia

PoS(ICHEP2012)431

---

[*] This research was funded in part by the Australian Research Council under Project ID DP0877916 and in part by the Project of Knowledge Innovation Program (PKIP) of Chinese Academy of Sciences, Grant No. KJCX2.YW.W10. The use of Monash University Sun Grid, a high-performance computing facility, is also gratefully acknowledged.

[†] Speaker.

1. Introduction

Cosmic ray observations provided puzzling deviations from theoretical predictions over the last decades. TS, AMS, CAPRICE, MASS, and HEAT [1] established an excess of high energy electrons/positrons. PAMELA confirmed these results by finding an excess over the theoretical predictions in the $e^-/(e^- + e^+)$ flux for $E > 10$ GeV [2]. An excess in the $e^- + e^+$ flux was found by AMS [3], PPB-BETS [4], and HESS [5]. Fermi-LAT confirmed this excess above 100 GeV [6]. PAMELA later confirmed this excess [7]. To explain the anomaly new physics was invoked ranging from modification of the cosmic ray propagation to postulating new sources. Ref. [8] summarizes these speculations. Whether the $e^{\pm}$ anomaly exists depends on the cosmic ray background prediction. This 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.

Motivated by traces of possible new physics in the Fermi-LAT data, we 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 measurements.

2. Galactic cosmic ray propagation

Galactic cosmic ray propagation is modeled by the diffusion-convection theory assuming homogeneous propagation of charged particles within the Galactic disk and it including energy loss effects [9]. 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 [10]

$$\begin{aligned} \frac{\partial \psi_a(\vec{r}, p, t)}{\partial t} &= Q_a(\vec{r}, p, t) + \nabla \cdot (D_{xx} \nabla \psi_a - \vec{V} \psi_a) - (\frac{1}{\tau_f} + \frac{1}{\tau_r}) \psi_a \\ &+ \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_a \right) - \frac{\partial}{\partial p} \left(\dot{p} \psi_a - \frac{p}{3} (\nabla \cdot \vec{V}) \psi_a \right). \end{aligned} \tag{2.1}$$

Here $q(\vec{r}, p, t)$ is the source term of primary and secondary cosmic ray contributions. The spatial diffusion coefficient has the form $D_{xx} = D_{0xx} \beta \left(\frac{R}{\mathrm{GeV}} \right)^{\delta}$, 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. Diffusion in momentum space is described by the coefficient D_{pp} which is related to D_{xx} [11, 12]. In Eq.(2.1), $\vec{V}$ is the convection velocity, and the parameter τ_f (τ_r) is the time-scale of the fragmentation loss (radioactive decay).

The GalProp numerical package solves the propagation equation numerically for $Z \geq 1$ nuclei, as well as for electrons and positrons [10]. GalProp has a number of free parameters which can be classified into a number of subsets: the diffusion of cosmic rays, the primary cosmic ray sources and radiative energy losses of these primary cosmic rays.

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:

$$P = \{\gamma^{e^-}, \gamma^{nucleus}, \delta_1, \delta_2, D_{0xx}\}. \tag{3.1}$$

Here δ_1 and δ_2 are spatial diffusion coefficients below and above a reference rigidity ρ_0, $\gamma_1^{e^-}$ and $\gamma_2^{nucleus}$ are the primary electron and nucleus injection indices which specify the steepness of the electron injection spectrum, $dq(p)/dp \propto p^{\gamma^{e^-}}$, and D_{0xx} determines the normalization of the spatial diffusion coefficient.

Our calculations confirmed the findings of the study in Ref. [13] that the $e^{\pm}$ flux is sensitive to the value of the Galactic plane height L. Indeed Ref. [11] has shown that there is a connection between L and D_{0xx}. Thus, varying the cylinder height is the same as the redefinition of D_{0xx} [14]. Realizing this we use D_{0xx} as free parameter and fix L to 4 kpc. We treat the normalizations of the e^-, e^+, $\overline{\text{p}}$/p, B/C, (SC+Ti+V)/Fe and Be-10/Be-9 fluxes as nuisance parameters.

When evaluating uncertainties, following Ref. [15], we ignore theory uncertainties and combine statistical and systematic experimental uncertainties as $\sigma_i^2 = \sigma_{i,statistical}^2 + \sigma_{i,systematic}^2$. 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. For these cases we rescale the statistical uncertainty to define $\sigma_i^2 = \sigma_{i,statistical}^2/\tau_i$. To remain consistent with Ref. [15], we set the 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 Ref. [12].

We included 219 of the most recent experimental data points in our statistical analysis. 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 remaining other 105 data points ($\overline{p}/p$, 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 that 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 non-$e^{\pm}$ related data to calculate a background prediction for the $e^{\pm}$ fluxes. Fig. 2 shows the calculated background. Experimental uncertainties are shown for Fermi-LAT and PAMELA as gray bands. Our background prediction is overlaid as magenta bands. According to our interpretation the deviation is a statistically significant signal of the presence of new physics in

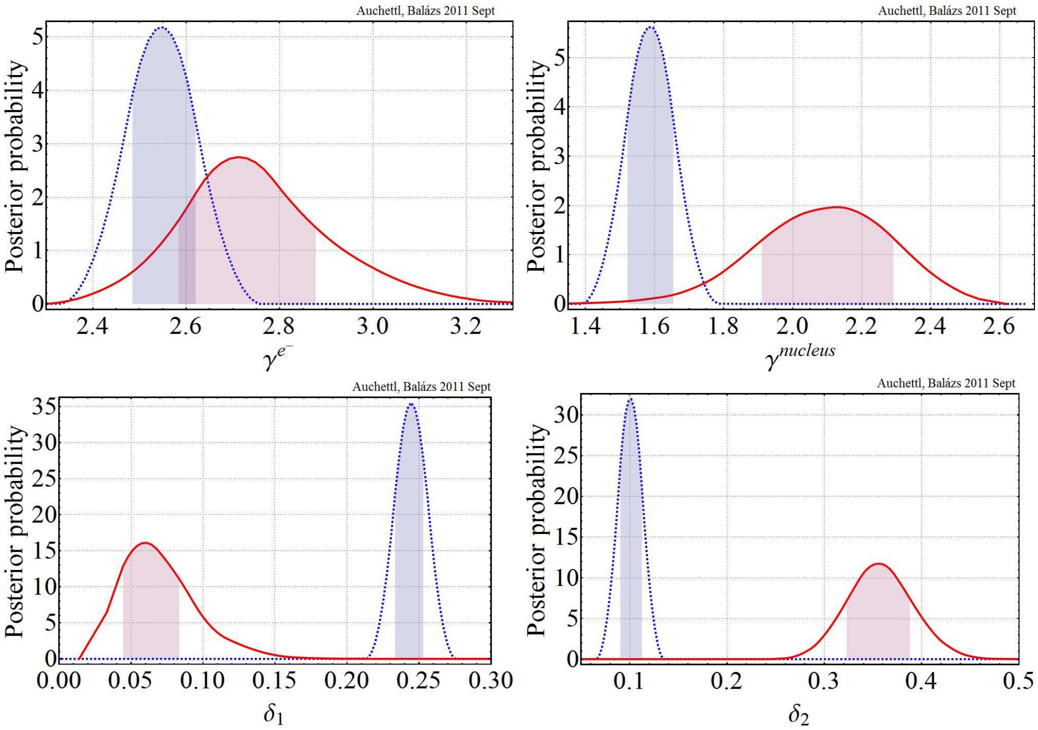

Figure 1: Marginalized posterior probability distributions of propagation parameters listed in Eq.(3.1). The dashed blue curves show results with likelihood functions containing $e^{\pm}$ flux data while the likelihood functions for the solid red curves contain only the rest of the cosmic ray data. Shaded 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.

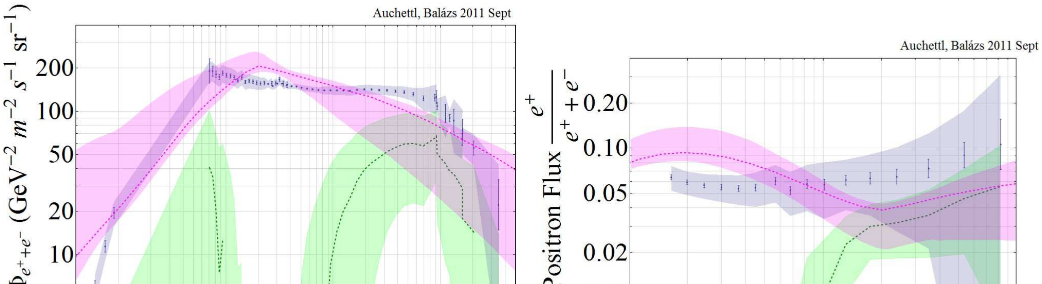

Figure 2: Electron-positron fluxes measured by Fermi-LAT and PAMELA (gray bands) with the extracted size of the $e^{\pm}$ anomaly (green bands). Combined statistical and systematic uncertainties are shown for Fermi-LAT and PAMELA e^-, while ($\tau = 0.2$) scaled statistical uncertainties are shown for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

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 [3]	0.60 - 0.91	3
	Fermi-LAT [6]	7.05 - 886	47
	HESS [5]	918 - 3480	9
$e^{+}/(e^{+}+e^{-})$	PAMELA [2]	1.65 - 82.40	16
e^{-}	PAMELA [7]	1.11 - 491.4	39
$\bar{p}$/p	PAMELA [16]	0.28 - 129	23
B/C	IMP8 [17]	0.03 - 0.11	7
	ISEE3 [18]	0.12 - 0.18	6
	Lezniak et al. [19]	0.30 - 0.50	2
	HEAO3 [20]	0.62 - 0.99	3
	PAMELA [21]	1.24 - 72.36	8
	CREAM [22]	91 - 1433	3
(Sc+Ti+V)/Fe	ACE [23]	0.14 - 35	20
	SANRIKU [24]	46 - 460	6
Be-10/Be-9	Wiedenbeck et al. [25]	0.003 - 0.029	3
	Garcia-Munoz et al. [26]	0.034 - 0.034	1
	Wiedenbeck et al. [25]	0.06 - 0.06	1
	ISOMAX98 [27]	0.08 - 0.08	1
	ACE-CRIS [28]	0.11 - 0.11	1
	ACE [29]	0.13 - 0.13	1
	AMS-02 [30]	0.15 - 9.03	15

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 from claiming 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. The central value and the 1 σ uncertainty of this signal is displayed as green dashed lines and bands in Fig. 2. 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 PAMELA due to the large uncertainties.

In Ref. [12] 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.

References

[1] Golden R L et al. (1994) *Astrophys. J.* **436**, 769–775. Alcaraz J et al. (2000) *Phys. Lett.* **B484**, 10–22. Boezio M et al. (2001) *Astrophys. J.* **561**, 787–799. Grimani C et al. (2002) *Astron. Astrophys.* **392**, 287–294. Barwick S W et al. (1997) *Astrophys. J.* **482**, L191–L194. Beatty J J et al. (2004) *Phys. Rev. Lett.* **93**, 241102.

[2] Adriani O et al (2010) *Astropart.Phys.* **34**, 1–11.

[3] Aguilar M et al. (2002) *Phys. Rept.* **366**, 331–405.

[4] Torii S et al. (2008) *Preprint* 0809.0760 [astro-ph].

[5] Aharonian F et al. (2008) *Phys. Rev. Lett.* **101**, 261104. Aharonian F et al. (2009) *Astron. Astrophys.* **508**, 561.

[6] Ackermann M et al. (2010) *Phys. Rev.* **D82**, 092004.

[7] Adriani O et al (2011) *Phys. Rev. Lett.* **106**, 201101.

[8] Serpico P D (2011) *Preprint* 1108.4827 [astro-ph.HE].

[9] Ginzburg V et al. (1990) *Astrophysics of cosmic rays* (Amsterdam) pp 534.

[10] Strong A W, Moskalenko I V and Ptuskin V S (2007) *Ann. Rev. Nucl. Part. Sci.* **57**, 285–327 .

[11] Seo E S and Ptuskin V S (1994) *Astrophys. J.* **431**, 705–714.

[12] Auchettl K and Balázs C (2012) *Astrophys. J.* **749**, 184.

[13] Cotta R C et al (2011) *JHEP* **01**, 064.

[14] Di Bernardo G et al (2011)*Astropart.Phys.* **34**, 528–538.

[15] Trotta R et al (2010) *The Astrophysical Journal* **729**, 106.

[16] Adriani O et al (2010) *Phys. Rev. Lett.* **105**, 121101.

[17] Moskalenko I V et al (2002) *Astrophys.J.* **565**, 280–296.

[18] Krombel K E and Wiedenbeck M E (1988) *Astrophys. J.* **328**, 940–953.

[19] Lezniak J A and Webber W R (1978) *Astrophys. J.* **223**, 676–696.

[20] Engelmann J J et al (1990) *Astronomy and Astrophysics* **233**, 96–111.

[21] Mocchiutti E et al (2008) *Proceeding of 21st European Cosmic Ray Symposium* 396–401.

[22] Ahn H S et al (2008) *Astropart. Phys.* **30**, 133–141.

[23] Davis A J et al (2000) *American Institute of Physics Conference Series* vol. 528, ed R A Mewaldt, J R Jokipii, M A Lee, E Möbius and T H Zurbuchen 421–424.

[24] Hareyama M (1999) *International Cosmic Ray Conference*, vol. 3 105–.

[25] Wiedenbeck M E and Greiner D E (1980 *The Astrophysical Journal Letters* **239**, L139–L142.

[26] Garcia-Munoz M et al (1981) *International Cosmic Ray Conference*, vol. 9 195–.

[27] Hams T et al (2001) *International Cosmic Ray Conference*, vol. 5 1655–.

[28] Davis A J et al (2000) *AIP Conference Proceedings* **528**, 421–424.

[29] Yanasak N E et al (2001) *Advances in Space Research* **27**, 727–736.

[30] Burger J (2004) *European Physical Journal C* **33**, 941–943.