Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: Luca Orusa *et al* 2021 *J. Phys.: Conf. Ser.* **2156** 012086

Journal of Physics: Conference Series **2156** (2022) 012086 doi:10.1088/1742-6596/2156/1/012086

Constraining positron emission from pulsar populations with AMS-02 data

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Abstract.
The cosmic-ray flux of positrons is measured with high precision by the space-borne particle spectrometer AMS-02. The hypothesis that pulsar wind nebulae (PWNe) can significantly contribute to the excess of the positron (e^+) cosmic-ray flux has been consolidated after the observation of a γ-ray emission at TeV energies of a few degree size around Geminga and Monogem PWNe. In this work we undertake massive simulations of galactic pulsars populations, adopting different distributions for their position in the Galaxy, intrinsic physical properties, pair emission models, in order to overcome the incompleteness of the ATNF catalogue. We fit the e^+ AMS-02 data together with a secondary component due to collisions of primary cosmic rays with the interstellar medium. We find that several mock galaxies have a pulsar population able to explain the observed e^+ flux, typically by few, bright sources. We determine the physical parameters of the pulsars dominating the e^+ flux, and assess the impact of different assumptions on radial distributions, spin-down properties, Galactic propagation scenarios and e^+ emission time.

1. Introduction

The observation of high-energetic cosmic-ray positrons with unprecedented precision by AMS-02 [2] suggests the presence of primary positron (e^+) sources in our Galaxy, as the observed flux exceeds the so-called secondary flux produced by inelastic collisions of cosmic-ray nuclei in the interstellar medium above about 10 GeV. Pulsars have been consolidating as significant factories of high-energy cosmic-ray electrons and positrons ($e^\pm$) in the Galaxy, and thus as main candidates to explain the e^+ excess. The idea of this work is to use the existing high-precision e^+ data to constrain the main properties of the Galactic pulsar population and of the PWN acceleration needed to explain the observed cosmic-ray fluxes. We here simulate a large number of realizations for the Galactic pulsar population in order to overcome the possible incompleteness of source catalogs, comparing different updated models which reproduce ATNF catalog observations. For each mock galaxy, we compute the resulting cosmic-ray e^+ flux at the Earth from the PWN population and we fit it to the AMS-02 data to determine the physical parameters of these populations which are able to explain the observed positron flux. We also asses the impact of different assumptions on the radial distribution of sources, spin-down properties and propagation scenarios. We refer to [1] for further details about this work.

2. Positrons from Galactic pulsars

Pulsars are rotating neutron stars with a strong surface magnetic field and magnetic dipole radiation is believed to provide a good description for its observed loss of rotational energy. The injection spectrum $Q(E,t)$ of $e^{\pm}$ at a time t is described as:

$$Q(E,t) = L(t)\left(\frac{E}{E_0}\right)^{-\gamma_e} \exp\left(-\frac{E}{E_c}\right) \qquad L(t) = \frac{L_0}{\left(1+\frac{t}{\tau_0}\right)^{\frac{n+1}{n-1}}} \tag{1}$$

where the cut-off energy E_c is fixed at 10^5 TeV, E_0 is fixed at 1 GeV, γ_e is the spectral index, τ_0 is the characteristic time scale and n defines the magnetic braking index. L_0 acts as a global normalization and depends on different quantities, in particular on the the initial rotational energy of a pulsar.

The flux of $e^{\pm}$ at the Earth for a source of age T, position $\mathbf{r_s}$ and at an observed energy E is given by:

$$\Phi_{e^{\pm}}(E, r=\mathbf{r}_{\odot}, t=T) = \frac{c}{4\pi}\int_0^T dt' \frac{b(E_s)}{b(E)} \frac{1}{(\pi\lambda^2(t',t,E))^{\frac{3}{2}}} \times \exp\left(-\frac{|\mathbf{r}_{\odot}-\mathbf{r_s}|^2}{\lambda(t',t,E)^2}\right) Q(E_s,t'). \tag{2}$$

The $b(E)$ term is the energy loss function, λ is the typical propagation scale length and E_s is the initial energy of $e^{\pm}$ that cool down to E in a loss time $\Delta\tau$:

$$\Delta\tau \equiv \int_E^{E_s} \frac{dE'}{b(E')} = t - t_{obs} \qquad \lambda^2 = \lambda(E,E_s)^2 \equiv 4\int_E^{E_s} dE' \frac{D(E')}{b(E')} = t - t_{obs} \tag{3}$$

where $D(E)$ is the diffusion coefficient. In our analysis we will consider as benchmark case (labeled as *Benchmark-prop*) the propagation parameters as derived in [3]. As a comparison, we will also implement the *SLIM-MED* model derived in [4]. For the *SLIM-MED* model, the flux coming from a single source is smoother with respect to the one obtained with the *Benchmark-prop*.

3. Simulations of Galactic pulsar populations

We simulate catalogs of Galactic pulsars, following the injection and propagation modeling described in Sec. 2. In all the simulations, the total number of sources is fixed at $N_{\rm PSR} = t_{max}\dot{N}_{PSR}$, where $t_{max} = 10^8$ yr is the maximum simulated age and $\dot{N}_{PSR} = 0.01$ yr^{-1} is the pulsar birth rate. Specifically, the fundamental parameters of each simulation are: the age of the source T, birth spin-down period P_0, surface magnetic field B, braking index n, angle between the magnetic field axis and rotational axis α, spectral index γ_e, efficiency η of conversion of the initial rotational energy into e^+ and the position $\mathbf{r}$ in Galactocentric coordinates. A summary of the simulated quantities is illustrated in Tab. 1. In order to assess the effects of different distributions for P_0, B, n, α, we consider the alternative model in [6] (`FK06` hereafter) and reported in Tab. 1. We sample $\mathbf{r}$ for each source adopting the radial surface density of pulsars $\rho_L(r)$ proposed by [7]. As a comparison, we will also consider the radial surface density $\rho_F(r)$ in [6]. The position $\mathbf{r}$ is fully determined by accounting for the spiral arm structure of the Milky Way according to the model of Ref. [6]. Here we recap the combinations of the different simulation setups described before and listed in Tab. 1:

`ModA` (benchmark). Spin-down and pulsar evolution properties are taken from `CB20` [5], while the radial distribution of sources is modelled with $\rho_L(r)$. η and γ_e are extracted from uniform distributions reported in Tab. 1, while the propagation in the Galaxy is taking into account with *Benchmark-prop* following Ref. [3].

Table 1. Summary of the quantities from which we build the mock pulsar catalogues. We report the distributions followed in the simulation of these parameters in our benchmark case, as well as the tested variations. See Sec. 3 for details.

PSR property	**Simulated quantity**	**Benchmark**	**Variations**
Age	T	Uniform [0, t_{max}]	-
		`CB20`[5]	`FK06`[6]
	P_0	Gaussian [0.3s; 0.15s]	-
Spin-down	log10(B)	Gaussian [12.85G; 0.55G]	Gaussian [12.65G; 0.55G]
	n	Uniform [2.5-3]	Constant [3]
	cosα	Uniform [0-1]	Constant [0]
$e^{\pm}$ injection	γ_e	Uniform [1.4-2.2]	-
	η	Uniform [0.01-0.1]	-
Radial distribution	**r**	$\rho_L(r)$ [7]	$\rho_F(r)$[6]

`ModB` (radial distribution effect). Same as `ModA` but with the radial surface density of sources $\rho_F(r)$ instead of $\rho_L(r)$ [6].

`ModC` (spin-down properties effect). Same as `ModA`, but spin-down properties are taken from `FK06` [6].

`ModD` (propagation effect). Same as `ModA` apart for propagation in the Galaxy, modelled as in Ref. [4] (their model *SLIM-MED*).

4. Results

For each simulation setup described in Sec. 3, we build and test 1000 simulations. We compute the e^+ flux at the Earth as the sum of the primary component due to pulsar emission (see Sect. 2 and Sect. 3), and a secondary component due to the fragmentation of cosmic rays on the nuclei of the ISM, taken from [3] and [4] consistently with the propagation model employed. In the fit procedure we renormalize the secondary contribution with a factor A_S, which we generously let to vary between 0.01 and 3, while the total flux generated by all pulsars is shifted by an overall normalization factor A_P. We fit AMS-02 data [2] above 10 GeV. The comparison of our predictions with the AMS-02 data is performed by a standard χ^2 minimization procedure.
The comparison through a fit of the predictions for the total e^+ flux to the AMS-02 data is performed for all the 1000 simulations built for each scenario `A-B-C-D`. In Tab. 2 we report the number of simulations, out of 1000, that produce different values of $\chi^2/d.o.f. = \chi^2_{\rm red}$ for each simulation setup. In all the tested setups, the number of mock galaxies with a $\chi^2_{\rm red} < 1$ (2) does not exceed 1% (4%). We present here some results for the total e^+ flux in our benchmark setup `ModA`. In Fig. 1 we plot the e^+ flux obtained for two illustrative simulated galaxies with $\chi^2_{\rm red} < 1$. The contributions from each pulsar, from the secondary emission and their sum are shown along with the AMS-02 data. All the good fits to the data find a value for A_S between 2 and 2.5, which might at least partially ascribable to an underestimation of spallation cross sections. The difference between `ModA` and `ModD` is relative only to the propagation and the energy losses modeling. `ModD` promotes a higher number of simulations to be compatible with

Table 2. Number of simulations (out of 1000) that produce a $\chi^2_{\rm red}$ smaller than a 2, 1.5 or 1, in the fit to AMS-02 data [2], for each simulation setup.

	$\chi^2_{\rm red} < 2$	$\chi^2_{\rm red} < 1.5$	$\chi^2_{\rm red} < 1$
ModA	15	8	4
ModB	30	19	6
ModC	15	10	3
ModD	42	25	10

the data: the *SLIM-MED* model produces fluxes from a single source which are smoother with respect to *Benchmark-prop*. Concerning the other simulation setups analysed, we do not find significant differences between ModA and ModC, and so between CB20 and FK06 pulsar evolution models. On the other hand, ModB promotes a higher number of simulations to be compatible with the data: since the $\rho_F(r)$ radial distribution predicts the presence of a higher number of sources in the spiral arms beside the Earth with respect to $\rho_L(r)$, for ModB there is a higher probability to simulate sources close to the Earth with characteristics compatible with the AMS-02 data. In these particular cases, the dominant contribution comes from sources in the distance ring between 1 and 3 kpc.

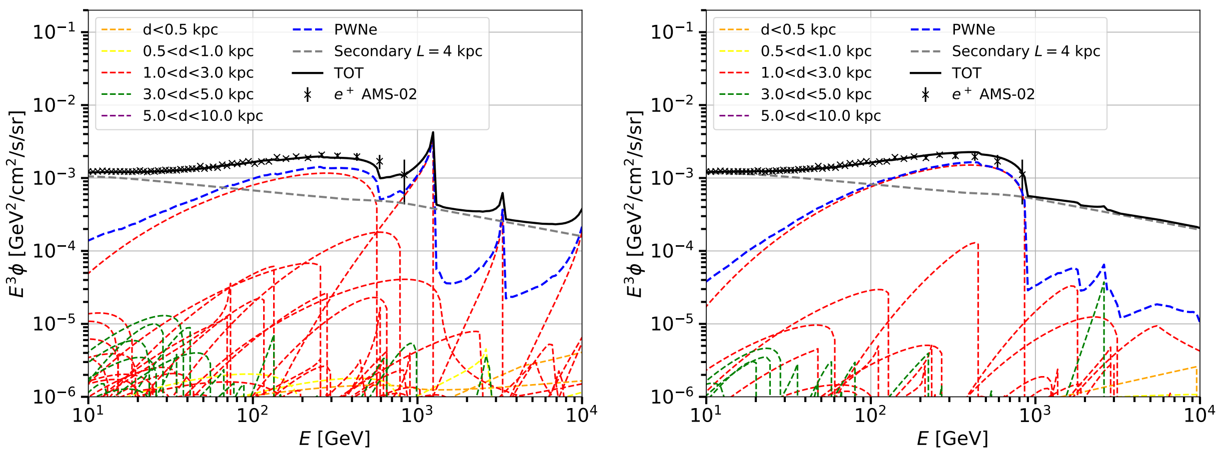

Figure 1. Comparison between the AMS-02 e^+ flux data [2] (black points) and the flux from secondary production (grey dashed line) and pulsars (blue dashed line) for two ModA realizations of the Galaxy with $\chi^2_{\rm red} < 1$. The contributions from each pulsar (reported with different colors depending on their distance from the Earth) are shown.

5. Mean number of PWNe dominating the e^+ flux

We inspect in this Section the average number of sources which contribute the most to the e^+ and thus can shape the AMS-02 flux adopting this criterion:
"we count all the sources that produce a flux higher than the experimental flux error in at least one energy bin above 10 GeV."
In Table 3 we report the average number of sources that satisfy the criterion, for all the simulated galaxies which provide a good fit to AMS-02 data ($\chi^2_{\rm red} < 1.5$). We obtain small numbers of sources responsible for most of the measured e^+, typically around 3, irrespective of the simulation

Table 3. Average numbers of sources that satisfy the criterion reported in Sec 5, for all the galaxies within each simulation setup, with $\chi^2_{\rm red} < 1.5$. For `ModA`, results are provided also for $\chi^2_{\rm red} < 1$ (left) and $\chi^2_{\rm red} < 2$ (right).

`ModA`	1.3/2.9/3.3
`ModB`	3.5
`ModC`	3.9
`ModD`	5.4

scheme. Scenarios with a large number of sources explaining the CR e^+ data are disfavored. This result is due to the fact that AMS-02 measures a smooth flux, therefore several PWNe contributing at different energies would create wiggles in the total flux which are not detected. Instead, a few sources generating a flux that covers a wide range of energies produce a smooth contribution compatible with the data. The change of propagation setup from `ModA` to `ModD`, produces an higher number of simulations that are compatible with the data, given the flux smoothing due to the alternative propagation setup. A slightly greater number of sources, tipically around 5, with respect to `ModA` satisfies the criterion for `ModD`. Dissecting results within `ModA`, we find that the mean number of sources decreases with decreasing $\chi^2_{\rm red}$, consistently with the requirement of a smooth trend of e^+ flux.

6. Conclusions

In this work we have performed several fits to the AMS-02 e^+ flux data testing a variety of simulated pulsar populations. The novelty of this paper is to use the existing high-precision e^+ data to constrain the main properties of the Galactic pulsar population and of the PWN acceleration needed to explain the observed cosmic-ray fluxes. We have simulated a large number of realizations for the Galactic pulsar population, comparing different updated models built on parameter distributions calibrated on observations, instead of ad-hoc realizations of pulsar characteristics. We used the AMS-02 data to determine the physical parameters of these populations, and of individual sources, which are able to explain the observed positron flux. We investigated the impact of different assumptions on the radial distribution of sources, spin-down properties, propagation scenarios and positron emission properties. Only a few galaxies for each setup with a small number of bright sources are compatible with the data. For further details about this work we refer to [1].

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