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ScienceDirect
Advances in Space Research 55 (2015) 1529–1536
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

The contribution of millisecond pulsars to the Galactic cosmic-ray lepton spectrum

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Received 27 October 2014; received in revised form 11 December 2014; accepted 19 December 2014
Available online 31 December 2014

Abstract

Pulsars are believed to be sources of relativistic electrons and positrons. The abundance of detections of γ-ray millisecond pulsars by *Fermi* Large Area Telescope coupled with their light curve characteristics that imply copious pair production in their magnetospheres, motivated us to investigate this old pulsar population as a source of Galactic electrons and positrons and their contribution to the enhancement in cosmic-ray positron flux at GeV energies. We use a population synthesis code to predict the source properties (number, position, and power) of the present-day Galactic millisecond pulsars, taking into account the latest *Fermi* and radio observations to calibrate the model output. Next, we simulate pair cascade spectra from these pulsars using a model that invokes an offset-dipole magnetic field. We assume free escape of the pairs from the pulsar environment. We then compute the cumulative spectrum of transported electrons and positrons at Earth, following their diffusion and energy losses as they propagate through the Galaxy. Our results indicate that the predicted particle flux increases for non-zero offsets of the magnetic polar caps. Comparing our predicted local interstellar spectrum and positron fraction to measurements by *AMS-02*, *PAMELA*, and *Fermi*, we find that millisecond pulsars are only modest contributors at a few tens of GeV, after which this leptonic spectral component cuts off. The positron fraction is therefore only slightly enhanced above 10 GeV relative to a background flux model. This implies that alternative sources such as young, nearby pulsars and supernova remnants should contribute additional primary positrons within the astrophysical scenario.

Keywords: Cosmic rays; Pulsars; Electrons; Positrons

1. Introduction

PAMELA was the first experiment to provide firm evidence of a rising positron fraction (PF), defined as $\phi(e^+)/[\phi(e^+)+\phi(e^-)]$, of the local (leptonic) interstellar spectrum above $\sim$10 GeV (Adriani, 2009). The *Fermi* Large Area Telescope (LAT) has confirmed this result (Ackermann, 2012), and *PAMELA* has recently extended the measurement range up to 300 GeV (Adriani, 2013). *AMS-02* has now provided a PF measurement in the range 0.5–350 GeV (Aguilar, 2013) for 18 months of data, and improved spectra for 30 months of data (Aguilar, 2014; Accardo, 2014), extending the PF up to 500 GeV and indicating a levelling off of this fraction with energy, as well as finding the PF to be consistent with isotropy.

Positrons are created during inelastic collisions involving cosmic-ray nuclei and intergalactic hydrogen, which produce charged pions that in turn decay into positrons,

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http://dx.doi.org/10.1016/j.asr.2014.12.022
0273-1177/

electrons, and neutrinos. The fraction of such a *secondary* positron component with respect to the total leptonic cosmic-ray spectrum is expected to smoothly decrease[2] with energy (e.g., Moskalenko and Strong, 1998). However, the *AMS-02* electron spectrum is softer than the positron flux in the range 20–200 GeV (Aguilar, 2014), and the measured PF rises with energy, pointing to nearby sources of *primary* positrons. Moreover, the rising PF can be ascribed to a hardening of the positron spectrum (up to 200 GeV, after which it softens with energy), and not a softening in electron spectrum above 10 GeV.

The purported additional source of primary positrons may be either of astrophysical or dark matter annihilation origin (e.g., Fan et al., 2010; Porter et al., 2011). The first case may include supernovae (e.g., Blasi, 2009; Delahaye et al., 2010), microquasar jets (Gupta and Torres, 2014) pulsar wind nebulae (e.g., Serpico, 2012), mature pulsars (Zhang and Cheng, 2001), and millisecond pulsars (MSPs; Kisaka and Kawanaka, 2012). The detection of a potential anisotropy in lepton flux may be an important discriminator between dark matter vs. pulsar (or supernova remnant) scenarios (Accardo, 2014), although this may depend on the number of individual sources that collectively contribute to the cosmic-ray lepton spectrum at Earth.

Alternatively, there have been several attempts to modify the standard Galactic cosmic-ray transport models in order to explain the observed rise in PF with energy purely by secondary positrons originating in the interstellar medium. Shaviv et al. (2009) demonstrated that an inhomogeneous distribution of SNRs, such as a strong concentration in the Galactic spiral arms, may explain the PF shape. Moskalenko (2013) pointed out that the concave shape of the primary electron spectrum of Shaviv et al. (2009) introduces an arguably artificial rise in the PF. Cowsik and Burch (2010) put forward a model that assumes a significant fraction of the boron below 10 GeV is generated through spallation of cosmic-ray nuclei in small regions around the sources; GeV positrons would then almost exclusively be generated through cosmic-ray interactions in the interstellar medium. Moskalenko (2013) noted that such sources should be observable as very bright GeV γ-ray sources with soft spectra, while the diffuse emission would be significantly dimmer than observed. This scenario is also at odds with current estimates of the supernova birth rate. Blum et al. (2013) found an upper bound to the positron flux by neglecting energy losses, arguing that the flattening of the PF seen by *AMS-02* around several hundred GeV is consistent with a purely secondary origin for the positrons. Moskalenko (2013) noted that their arguments imply quite hard injection spectra for primary nuclei, in contradiction to γ-ray observations of SNRs. A very fast escape time for the positrons is furthermore implied, and if this is extrapolated to higher energies, it would lead to a large cosmic-ray anisotropy, which has not been observed.

The presence of γ-ray photons and intense magnetic fields in pulsar magnetospheres facilitate copious electron–positron pair production (Sturrock, 1971; Daugherty and Harding, 1982), making pulsars prime candidate sources of primary Galactic leptons. We previously studied the contribution to the local electron spectrum by the nearby MSP PSR J0437−4715 (assuming a pair-starved potential) as well as Geminga, and found that the latter may contribute significantly, depending on model parameters (Büsching et al., 2008a). Büsching et al. (2008b) also noted that Geminga and PSR B0656+14 may be the dominant contributors to the local positron flux, and may be responsible for an anisotropy of up to a few percent in this flux component, depending on model parameters. Moskalenko (2013) however notes that to date the pulsar scenario lacks convincing calculations of the number of ejected particles and their spectrum.

In this paper, we carefully assess the contribution of MSPs (excluding those found in the globular clusters) to the cosmic-ray lepton spectrum at Earth, given the large number of *Fermi*-detected Galactic γ-ray MSPs (Abdo, 2013), and the fact that their measured light curves imply abundant pair production even for this much older pulsar class (Venter et al., 2009). We use a population synthesis code to predict the source properties (Section 2) and a pair cascade code to find realistic injected pair spectra (Section 3). We next combine inverse Compton (IC) scattering of leptons on the local interstellar radiation field (ISRF; Section 4) and their synchrotron radiation (SR) in the Galactic *B*-field (Section 5) into an effective loss term (Section 6), and use this together with a prescription for particle diffusion when solving a transport equation (Section 7) to calculate the spectra at Earth (Section 8). We discuss our results Section 9. More details will be provided in Venter et al. (submitted for publication).

2. Present-day distribution of Galactic MSPs

We implement the results of a new study by Gonthier (in preparation) of the population synthesis of radio and γ-ray MSPs that lead to the present-day distribution of MSPs. This distribution of MSPs is assumed to be an equilibrated one within the Galaxy. Its evolution has been described in Section 3 of Story et al., 2007, hereafter SGH, where the radial (ρ in cylindrical coordinates) distribution was assumed to be that of the work of Paczyński (1990), with a radial scaling of 4.5 kpc and a scale height of 200 pc instead of 75 pc used in that work. In addition, we implement the supernova kick velocity model of Hobbs et al. (2005) using a Maxwellian distribution with a width of 70 km s^{-1} (resulting in an average of speed of 110 km s^{-1}). The Galaxy is seeded with MSPs treated as point particles with ages going back to the past 12 Gyr assuming a constant birth rate of 4.5×10^{-4} MSPs per century as obtained in SGH. The MSPs are evolved in the Galactic potential

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[2] This, however, depends on model assumptions, i.e., a concave electron spectrum may lead to a rising PF.