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Pulsar Wind Nebulae and Cosmic Rays: A Bedtime Story

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Abstract

The role pulsar wind nebulae play in producing our locally observed cosmic ray spectrum remains murky, yet intriguing. Pulsar wind nebulae are born and evolve in conjunction with SNRs, which are favored sites of Galactic cosmic ray acceleration. As a result they frequently complicate interpretation of the gamma-ray emission seen from SNRs. However, pulsar wind nebulae may also contribute directly to the local cosmic ray spectrum, particularly the leptonic component. This paper reviews the current thinking on pulsar wind nebulae and their connection to cosmic ray production from an observational perspective. It also considers how both future technologies and new ways of analyzing existing data can help us to better address the relevant theoretical questions. A number of key points will be illustrated with recent results from the VHE (E > 100 GeV) gamma-ray observatory VERITAS.

1. Introduction

The discovery of cosmic rays in the early twentieth century [1, 2] inaugurated a decades-long, serialized mystery story that has yet to be completed. At the heart of the mystery lies a set of of simple questions. What particles appear in the cosmic ray spectrum that we see from Earth? Where do these particles originate? How are they accelerated? In recent decades direct cosmic ray observations have brought us a wealth of information on the cosmic ray spectrum and its composition, clues to the types of environments in which cosmic rays are born. The interaction of these particles with interstellar magnetic fields, however, prevents them from being traced back to their point of origin.

In order to pursue the other half of this mystery—the nature of cosmic ray accelerators—we must use the secondary photon radiation produced in these cosmic ray nurseries. These high-energy (300 MeV - 100 GeV) and very high-energy (VHE; $E > 100$ GeV) gamma rays are not deflected by interstellar magnetic fields and can be used to map cosmic ray populations in and near their parent accelerators. The different processes by which relativistic cosmic ray electrons, protons, and heavier nuclei produce high-energy gamma rays leave characteristic imprints on the gamma-ray energy spectrum of particular astrophysical accelerators. These features may be used to constrain the composition and energy spectrum of accelerated particle populations.

The local cosmic ray spectrum is known to be a mix of protons and heavier nuclei, with a smaller admixture of leptons. A mix of astrophysical accelerators within and outside our Galaxy is believed to contribute, including shocks arising in supernova remnants (SNRs), shocks formed by interacting high-velocity winds from massive stars [3], pulsars, and active galactic nuclei (AGN). We focus here on a single subplot of a much larger story—the role played by pulsar wind nebulae (PWNe) in our quest to understand the Galactic cosmic ray spectrum.

2. Dramatis Personae

No single gamma-ray observatory provides a complete picture of the gamma-ray sky at all energies and spatial scales. The Fermi Gamma-ray Space Telescope (*Fermi LAT*) can map the entire gamma-ray sky between 300 MeV and 500 GeV over all spatial scales, with an angular resolution that ranges from 0.1° to 1° depending

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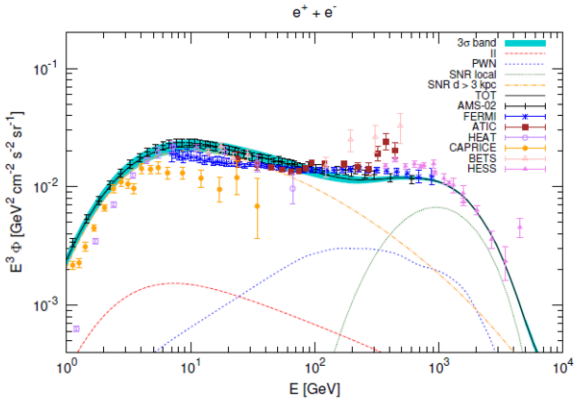

Figure 1: Comparison to extant data from AMS-02 [4], *Fermi LAT* [5], ATIC [6], HEAT [7], CAPRICE[8], BETS[9], and H.E.S.S.[10] of a model considering contributions to the $e^{\pm}$ flux from the following categories: e^{-} from distant (> 3 kpc) SNRs (dot-dashed yellow) and local SNRs (dotted green), secondary $e^{\pm}$ (long dashed red) and $e^{\pm}$ from PWNe (short dashed blue). The model is derived from a simultaneous fit to all AMS-02 data. Reproduced from [11]. (A color version of this figure is available in the online journal).

on energy. However, *Fermi LAT* data become photon-poor above 10 GeV. Efficient detection of gamma rays above 100 GeV requires ground-based gamma-ray observatories. Arrays of imaging atmospheric Cherenkov telescopes (IACTs), treat the atmosphere as the sensitive volume of an electromagnetic calorimeter. Sampling the pool of Cherenkov light produced by atmospheric showers from multiple views permits better reconstruction of the arrival direction and energy of the primary gamma ray [12]. Currently-operating IACT arrays include VERITAS and MAGIC in the northern hemisphere and H.E.S.S. in the southern hemisphere. These instruments have fields of view between 2° and 5°. While the precise energy threshold varies by observatory, all are sensitive between 100 GeV and 10 TeV. RPC carpet detectors such as ARGO-YBJ [13] and water Cherenkov detectors, such as the recently-decommissioned Milagro [14, 15] and the newly-commissioned HAWC [16] have wide fields of view and the best access to energies above 10 TeV, effectively complementing the IACTs.

2.1. *VERITAS*

VERITAS, an array of four 12-m IACTs in southern Arizona, is currently the most sensitive TeV gamma-ray instrument in the northern hemisphere. Each of the four cameras has a 3.5°-diameter field of view (giving the array an overall field of view of 3.5°) and is equipped with 499-pixel photomultiplier tube camera. VERITAS has an angular resolution (68% containment) of better than 0.1° at 1 TeV and is sensitive to sources with integral fluxes less than 1% of the Crab Nebula flux with less than 30 hours of observation time. VERITAS has been in continuous operation as a four-telescope array since January 2007. It underwent a series of upgrades in the period between 2009-2012 that increased the instrument's sensitivity [17] and decreased its energy threshold.

2.2. *Pulsar Wind Nebulae*

The rapidly spinning neutron stars known as pulsars are thought to be some of the most powerful sources of electrons and positrons ($e^{\pm}$) in the Galaxy [11]. The pulsar is thought to possess a strong, rotating magnetic field that generates a powerful electric field, which then rips particles free from the pulsar surface. Once accelerated, these charged particles can produce further particle-antiparticle pairs through curvature radiation, creating a relativistic charged-particle wind. Since the pulsar is created by a supernova explosion, both the pulsar and its wind are initially located within the SNR. The interaction of the pulsar wind with the slower supernova ejecta creates a *termination shock*. The magnetized, relativistic plasma between the termination shock and the ejecta is known as the pulsar wind nebula (PWN). Particles and antiparticles are accelerated to very high energies before becoming trapped by the PWN magnetic field. Over time the PWN magnetic field weakens and these particles are injected into the interstellar medium (ISM).

3. Pulsar Wind Nebulae and the Positron Excess

The origin of cosmic ray electrons and positrons, like the origin of the protons and heavier nuclei that make up the dominant portion of the terrestrial cosmic ray spectrum, is a question of great interest. Typical models of the cosmic ray lepton spectrum invoke the following contributions, as illustrated in Figure 1: electrons produced in SNRs and secondary electrons and positrons from spallation reactions of hadronic cosmic rays with the ISM. The secondary $e^{\pm}$ components are expected to fall off quickly above 100 GeV; distant SNRs also contribute strongly to the electron spectrum below this energy. Electrons produced in local SNRs are expected to fill out the electron spectrum above 100 GeV. In this picture the fraction of positrons in the cosmic ray lepton spectrum should decrease with increasing energy, in contradiction to results from ATIC [6], PAMELA [18],

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