

# Constraining the Origin of Local Positrons with HAWC TeV Gamma-Ray Observations of Two Nearby Pulsar Wind Nebulae

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Cosmic-ray positrons are charged antiparticles that strike Earth's atmosphere isotropically. At energies below several GeV they are produced by cosmic-ray protons interacting with nearby interstellar matter. At higher energies, an unexpected and unexplained excess above the proton-induced background has been detected by several satellites, including PAMELA, AMS-02 and Fermi. Due to energy losses in interstellar magnetic and radiation fields, the highest-energy positrons observed must have originated in our immediate Galactic neighborhood. This excess has been theorized to be originated from nearby astrophysical sources, dark matter, or new modes of cosmic-ray secondary production. Amongst the astrophysical sources, pulsars as Geminga and PSR B0656+14 have been proposed to be contributors to this excess. The HAWC Gamma-Ray Observatory reported the discovery of TeV gamma-ray emission extending several degrees around the positions of Geminga and PSR B0656+14 pulsars. Using the morphological and spectral measurements of these two VHE gamma-ray sources, we determine the diffusion coefficient of electrons escaping them and their contribution to the positron flux measured at Earth. For this assumption of isotropic diffusion, we find that neither of these sources make an appreciable contribution to the locally measured positron flux.

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## 1. Introduction

Cosmic rays (CRs) are high-energy charged particles that strike the atmosphere almost isotropically. They are composed by protons and helium nuclei (99%), heavier nuclei, electrons ( $e^-$ ), positrons ( $e^+$ ), antiprotons and neutrinos. There are galactic propagation models that reproduce the all-electron ( $e^\pm$ ) CR energy. However, the  $e^+$  content in the total  $e^\pm$  flux above 10 GeV (also known as “positron excess”) measured by PAMELA and AMS amongst others, can only be explained if there is a source injecting them. Moreover, taking into account standard diffusion and cooling of  $e^\pm$ , the extension of the  $e^\pm$  spectrum up to TeV energies can only be explained if the source is nearby ( $\sim$ hundreds of parsecs) and middle age ( $\sim$ hundred of kyr). Pulsars, as factories of  $e^\pm$ , are the most suitable candidates to explain the origin of this excess. Amongst the known pulsars, Geminga and PSR J0659+14 are the two best candidates due to their distance and age. Since  $e^\pm$  are charged particles, their arrival direction does not point to their origin because they are deflected by magnetic fields. One of the ways to study sources of CRs is to analyse the neutral subproducts of CR collisions such as gamma rays. Establish that pulsars are not the origin of this excess would point to more exotic processes such as galactic jets [1] or dark matter [2]. Milagro reported very-high-energy (VHE;  $E > 100$  GeV) gamma-ray emission from Geminga in 2009 [3]. The emission was very extended ( $2.6^\circ$ ) and had a significance of  $6.3\sigma$ . The Tibet Air shower array reported an excess of  $2.2\sigma$  at the location of the pulsar but did not report extended emission [4]. Imaging Atmospheric Cherenkov Telescopes (IACTs) have observed Geminga without significant detection [5, 6].

## 2. HAWC Observatory and dataset

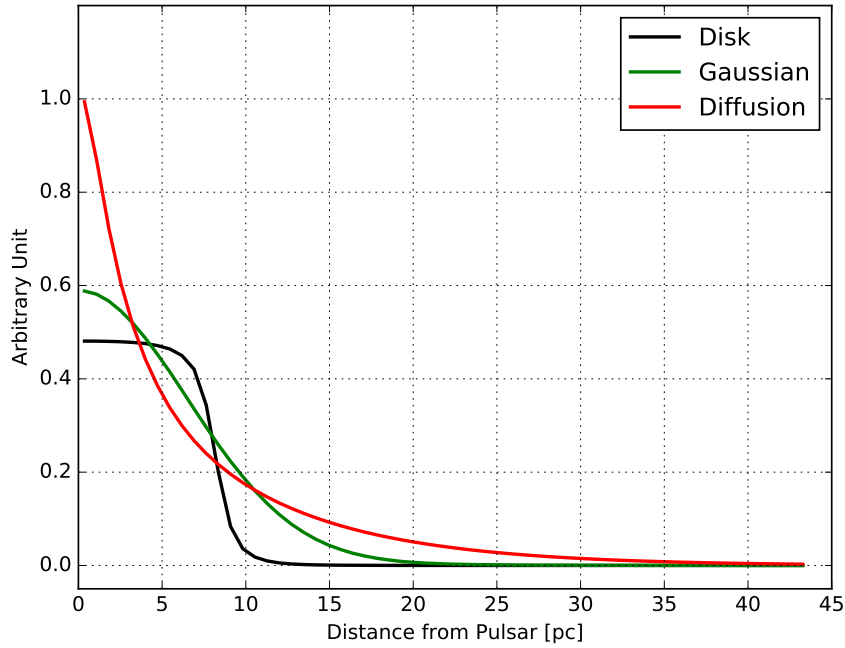
The HAWC Gamma-Ray Observatory is located at Sierra Negra, Mexico at 4 100 m a.s.l., and is sensitive to gamma rays and cosmic rays in the energy range from 100 GeV to 100 TeV [7]. It is composed by 300 optically isolated tanks covering an area of 22 000 m<sup>2</sup>. Each one of these Water Cherenkov Detectors (WCD) consists of a metallic cylinder of 7.3 m diameter and 4.5 m height containing 180 000 liters of water. They are equipped with one 10" PMT at the center and three 8" PMTs surrounding the central one. The array has a 2 sr field of view with  $>95\%$  uptime. It started operation in its full configuration in March 2015. The current analysis was performed using 17 months of data with the complete HAWC array, the same dataset used for the HAWC 2HWC catalog [8]. In the catalog, the detection of extended emission in the vicinity of Geminga and PSR B0656+14 was reported associated with the HAWC source 2HWC J0635+180 and 2HWC J0700+143.

## 3. Results

The Geminga pulsar (PSR J0633+1746) is an isolated neutron star in the Gemini constellation. The characteristic age of the pulsar is  $3.42 \times 10^5$  yr and the distance of 250 pc with a spin-down luminosity of  $3.26 \times 10^{34}$  erg s<sup>-1</sup> [9]. The pulsar B0656+14 is also an isolated neutron star which has been associated with the large (25 degree) supernova remnant covering the Gemini and Monoceros constellations called the “Monogem ring”. Some authors speculated that the Monogem Ring SNR

could be the long-searched-for source of the highest energy protons producing the “knee” feature in the cosmic-ray spectrum [10]. PSR B0656+14 has a characteristic age is  $1.1 \times 10^5$  yr, the distance to Earth is 288 pc, and the spin-down luminosity is  $3.8 \times 10^{34}$  erg s<sup>-1</sup> [9].

For the analysis, we tested different morphological assumptions as shown in Fig. 2. The first morphology approximated the source as extended disks where a constant (average) flux of gamma-rays fitted within a distance from the source center location. The second morphology is a symmetrical two-dimensional Gaussian. In this case, the fitted flux of gamma-rays depends on the distance from the source center location as following a 2D-Gaussian. Apart from these two morphologies, which do not depend on physical assumptions, a third one based on [11] assumes electron and positron pairs diffusing into the interstellar medium around the pulsar, producing gamma rays through inverse Compton scattering of CMB photons.



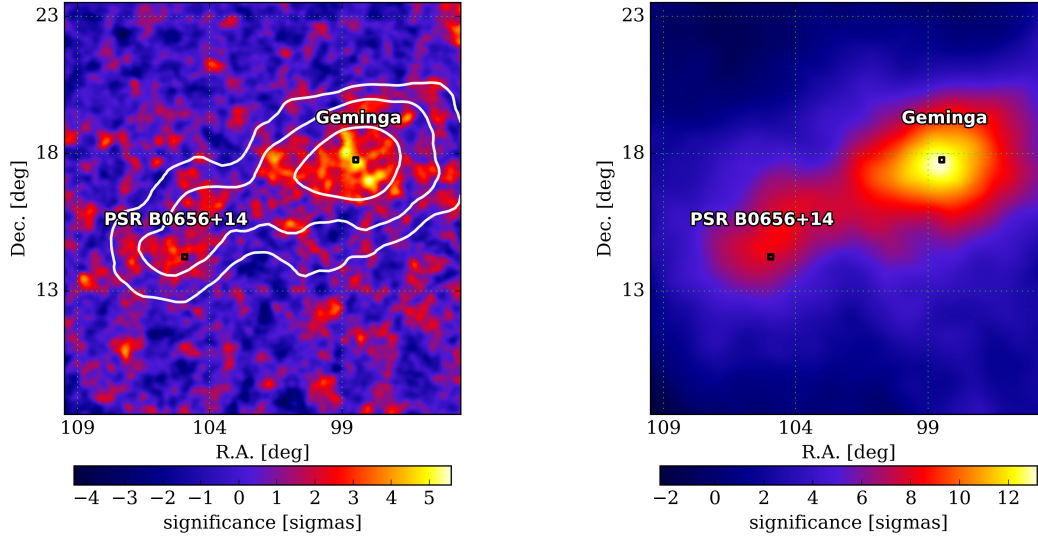
**Figure 1:** Geminga flux per surface unit for different radial distances. Overlaid are the three morphological models tested.

The results show that the emission from the Geminga location reaches  $13.1 \sigma$  when a diffusion model morphology is used (see Fig. 1). In addition, a similar extended TeV gamma-ray emission in the vicinity of PSR B0656+14 has been detected at an  $8.1 \sigma$  level. Unlike Geminga, the extended emission of PSR B0656+14 was not reported before by any gamma-ray experiment.

A first estimate of the source gamma-ray flux was provided in the recent HAWC catalog [8]. The final result using a diffusion model morphology can be found in [12].

#### 4. Conclusion

HAWC carried out morphological and spectral studies using the 17 months dataset of the Geminga and PSR B0656+14 region. These studies provide information about the diffusion co-



**Figure 2:** Significance map for the Geminga and PSR B0656+14 region convolved with the point spread function (left) and with the particle diffusion morphology (right).

efficient and gamma-ray spectrum which can be used as input parameters for the EDGE code [13]. EDGE takes into account the theory of electron diffusion, and computes the expected positron flux produced at the Earth by a pulsar. The derived positron spectrum at Earth considering the measurements of Geminga and PSR B0656+14 by HAWC and further conclusions are shown in [12]

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