Analysis of Highest Energy Gamma-Ray Emission from the Geminga Pulsar Wind Nebula

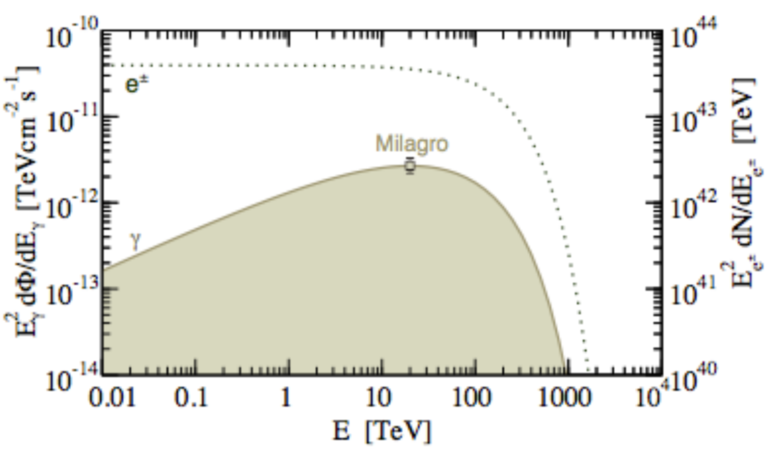
By: Kelci Mohrman Advisor: Dr. Petra Huentemeyer

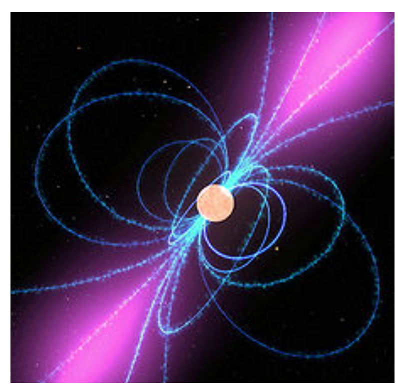
Introduction

Geminga (PSR J0633+1746) is a rotating neutron star, called a pulsar, located in the direction of the constellation Gemini, approximately 160 parsecs away from earth [1]. One of the closest pulsars to earth, Geminga is also one of the brightest point sources of MeV–GeV gamma rays in the sky [2]. Geminga is surrounded by a pulsar wind nebula (PWN), which accelerates particles to high energies and emits constant gamma radiation at TeV energies [2].

The PAMELA detector, launched into orbit in 2006, discovered an excess of positrons in the GeV to multi-GeV cosmic-ray flux [3], which was confirmed by NASA's Alpha Magnetic Spectrometer (AMS) [4]. It has been proposed that this excess is due to interactions with dark matter; another proposed explanation is that the excess is due to the positrons accelerated by the Geminga PWN [2]. Geminga, because of its proximity to earth, appears as an extended source in TeV gamma-ray sky maps [5]. The extended TeV emission has been previously measured by the Milagro ground based water Cherenkov radiation telescope; however, a dedicated extended source analysis of the emission from the Geminga nebula using GeV data from NASA's Fermi Gamma-ray Space Telescope has not yet been presented. This proposed summer research project will use all of the Fermi data in GeV available to date in order to study a possible extended emission from Geminga's PWN. Figure 1 shows a simulated gamma-ray energy spectrum of the Geminga PWN in the GeV to TeV range which would explain the positron excess observed by PAMELA, but which is anchored to only a single Milagro data point [6]. The goal of this project is to ascertain additional data points to populate the plot in Figure 1 in order to constrain the model proposed in [6] and thus to help distinguish the pulsar wind nebula explanation from the dark matter explanation of the observed positron excess.

Figure 1 (left): Energy spectrum of the Geminga PWN emission explaining the positron excess observed in the cosmic-ray flux [6]. Figure 2 (right): Depiction of a pulsar's magnetic field (blue) and gamma-ray emission (purple) [7].





Background

When a large star (more than 8 times the mass of our sun) has used up most of its fuel and can no longer sustain the fusion processes that power the star, the outward pressure caused by fusion will no longer be able to counterbalance the inward pressure of its own gravity, and the star will collapse upon itself in a violent event known as a supernova. If the star had been within 8 to 25 times the mas of the sun, the core left behind from the supernova will exist as a neutron star. Due to the conservation of angular momentum, the neutron star rotates extremely rapidly. A neutron star has a very concentrated magnetic field, and if the north and south poles of the magnetic field are not aligned with the axis of rotation, powerful electric fields are created. [8]

These electric fields accelerate charged particles (such as electrons and protons), which emit radiation in the gamma-ray spectrum. Viewed from earth, a rotating neutron star appears to pulse each time this beam of radiation sweeps past our view. This basic model for the pulsar is depicted in Figure 2. The disturbance in the interstellar medium that the pulsar creates will cause a standing shock wave to form around the pulsar, known as a pulsar wind nebula. This shock wave accelerates particles (probably electrons and positrons) [2] to very high energies, which will in turn cause the emission of constant radiation, as opposed to the pulsating radiation we observe from the pulsar itself. Because this steady emission is due to the accelerated particles, studying the gamma rays emitted from the nebula will help to form a more comprehensive understanding of the accelerated particles ejected by the wind nebula.

Objectives

The purpose of this project is to measure and to analyze the steady, extended gamma-ray emission of the Geminga PWN in order to compare the resulting energy spectrum to the model presented in Figure 1. Since the particles accelerated and emitted by the wind nebula have been proposed to be responsible for the observed positron excess, studying the gamma-ray emissions of the wind nebula could help to determine if this explanation can be substantiated. The objective of this project is to analyze the Fermi data in the extended region around Geminga in order to compare them with the curve normalized using the Milagro data from the extended region. If emission is found, the new data points may be added to the spectrum; if no emission in this range is identified, an upper limit will be calculated and will help to constrain the energy spectrum of the Geminga PWN between GeV and TeV. Milagro was succeeded by the more sensitive High-Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory [9], and, depending on the progress of the proposed summer research, a joint fit with Fermi data in GeV and HAWC data in TeV may be performed to provide even more complete and detailed information about the energy spectrum of Geminga.

Methods

Fermi data, available to be downloaded from a NASA website [10], will be used to search for extended steady emission of Geminga's PWN. The MeV–TeV emission from Geminga is dominated by the pulsating emission, but this is cut off at a few GeV [11], so emission found at higher energies (especially if extended) is likely due to the wind nebula. Thus, the proposed analysis will focus on higher energy events (approximately 10 GeV to a few hundred GeV) in Fermi data. Furthermore, since the nebula is extended, a larger area around Geminga may be integrated to search for the nebula emission. If emission is successfully identified, the data points may be added to the Milagro point. If no emission is located, the identified upper limit will help to constrain the energy spectrum. The means through which this analysis will take place are the Fermi Science Tools, NASA's publicly available software designed to analyze the Fermi data [12]. The method used to analyze these data is a maximum likelihood fit, which establishes the significance of a source's variance above its surroundings by fitting a combined extended source and background model to the Fermi data [13]. The Multi-Mission Maximum Likelihood framework (3ML), developed to coherently combine data from diverse experiments, endeavors to correct for systematic and statistical uncertainties specific to each experiment by incorporating appropriate models for the different detector responses [14], and thus may be used to perform a joint fit with Fermi data in GeV and HAWC data in TeV.

Summary

The subject of this summer research project is to search for the steady gamma-ray emission of the Geminga PWN by using Fermi data at energies above Geminga's pulsating emission in the extended region around the pulsar. Since the gamma-ray emission of the nebula is due to the electrons and positrons accelerated by the nebula, developing a more accurate representation of the nebula's gamma-ray energy spectrum may help to distinguish the pulsar wind nebula explanation from the dark matter explanation for the observed positron excess.

References

[1] G. F. Bignami and P. A. Caraveo, "Geminga: Its Phenomenology, Its Fraternity, and Its Physics," *Annual Reviews of Astronomy Astrophysics,* vol. 34, Sept 1996, p 349.

[2] H. Yüksel, M. D. Kistler, T. Stanev, "TeV Gamma Rays from Geminga and the Origin of the GeV Positron Excess," *Physical Review Letters*, vol. 103, July 2009, p 1. (accessed through arXiv.org)

[3] O. Andriani et al., "Observations of an Anomalous Positron Abundance in the Cosmic Radiation," *Nature*, April 2009, p 2. (accessed through arXive.org)

[4] AMS-02.org: http://www.ams02.org/2014/09/new-results-from-the-alpha-magnetic-spectrometer-on-the-international-space-station/

[5] A. A. Abdo et al, "Milagro Observations of Multi-TeV Emissions from Galactic Sources in the Fermi Bright Source List," *Astrophysical Journal Letters*, July 2009, p 2. (accessed through arXiv.org)

[6] H. Yüksel, M. D. Kistler, T. Stanev, "TeV Gamma Rays from Geminga and the Origin of the GeV Positron Excess," *Physical Review Letters*, vol. 103, July 2009, p 2. (accessed through arXiv.org)

[7] Image Credit: NASA, Fermi: http://www.nasa.gov/mission_pages/GLAST/news/gr_pulsar.html.

[8] Commins, N. F. (2013). Discovering the Essential Universe (5th ed., pp. 301-311). New York, NY: W. H. Freeman.

[9] HAWC Gamma-Ray observatory website: http://www.hawc-observatory.org

[10] Fermi data: http://fermi.gsfc.nasa.gov/ssc/data/

[11] A. A. Abdo et al., "Fermi-LAT Observations of the Geminga Pulsar," *The Astrophysical Journal*, vol 720, Sept 2010, p 279. (accessed through arXiv.org)

[12] Fermi science tools: http://fermi.gsfc.nasa.gov/ssc/data/analysis/

[13] P. L. Nolan et al., "Fermi Large Area Telescope Second Source Catalog," *The Astrophysical Journal Supplement Series,* April 2012.

[14] G. Vianello et al., "The Multi-Mission Maximum Likelihood Framework (3ML)," *Proceedings of Science,* July 2015. (accessed through arXiv.org)