Probing the Emission Mechanism of Pulsar Wind Nebulae with GLAST

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Abstract

Highly energetic pulsars form wind nebulae that generate emission visible from radio to gamma-ray energies. The relationships of the pulsar, the wind nebula, the surrounding supernova remnant, and the environment containing the system are complex, but these objects offer a unique opportunity to probe the acceleration processes common in nonthermal astrophysical sources. Some are close enough that the spatial resolution and sensitivity of the current X-ray missions have produced stunning results that show the overall structure of the nebula as well as compact features within it. Some of the pulsar wind nebulae (PWNe) detected at energies above 100 GeV have a sufficiently large angular extent that ground-based gamma-ray telescopes can resolve the nebula and large features. The energy band from MeV to GeV was previously explored by EGRET on the Compton Gamma Ray Observatory. This mission detected many sources that were not initially identified with radio or X-ray counterparts. A few of these have recently been associated with new X-ray and TeV detections of PWNe and have even prompted new discoveries of faint radio pulsars. The Large Area Telescope, an instrument on the Gamma-ray Large Area Space Telescope (GLAST), will survey the sky at energies above 100 MeV with improved sensitivity and angular resolution over EGRET. GLAST will launch in 2007 and is expected to detect numerous new gamma-ray sources. Some number of these will be pulsars and PWNe. Because PWNe allow observations of spatially resolved regions of emission and sensitive spectral measurements in different frequency bands, this class of sources is beginning to provide a powerful test of astrophysical particle acceleration models, especially if the properties of the pulsar providing the central engine are known. In order to extract the science of the underlying pulsar and wind nebula emission mechanisms, it will be important to identify candidate sources in GLAST with existing X-ray and TeV PWNe and to determine which of the new gamma-ray sources lacking identification are the most promising targets for follow-up observations at other wavelengths.

1 Introduction

This proposal intends to address the question of the mechanism for particle acceleration in pulsar-driven wind nebulae through the study of these objects with the Gamma-Ray Large Area Space Telescope (GLAST) and in combination with observations in the X-ray and TeV energy bands. The physics and observed properties of the pulsar wind nebula and the particle acceleration that occurs in this environment are first discussed. Recent high energy results and the implications for the observations that will be made by GLAST are then presented. My background work and its relation to the proposed study are included and followed by a discussion of the specific plan for identifying pulsar wind nebulae candidates with GLAST. Finally, the expectation for the results and how they may be applied to the multiwavelength work that will be done with GLAST are given.

2 Statement of the Problem

2.1 Overview of Pulsar Wind Nebulae

Pulsars are one of the most intriguing types of astrophysical sources detected at high energies. A pulsar forms in the supernova death of a massive star that collapses to form a compact neutron star. The expanding shock wave of the explosion moves away from the pulsar birthplace. Meanwhile, the pulsar system stabilizes in such a way that the neutron star is rotating rapidly within a strong and highly-ordered magnetic field. A powerful electromagnetic dynamo is formed and the acceleration of electrons and positrons in the neutron star magnetosphere generates a powerful pulsed beam of emission. The period of the beam ranges from milliseconds for some pulsars to a few seconds for others and has been measured at wavelengths ranging from radio to X-rays or in some cases even gamma rays. Despite decades of observations in the radio band, some important aspects of how and where the particle acceleration in pulsars occurs are not understood.

Several pieces of information are key to modeling the emission of the pulsar. The properties that we know best are those well-measured in the radio band, the pulse period, the derivative of the period, and the pulsar profile. The rotation of the neutron star slows over time as is evident in the increasing period Measurements of both the period and derivative are used to estimate the characteristic age of the pulsar, the output power, and the magnetic field. Another piece of key information is the geometry of the pulsar, or the positions of the spin and magnetic axes and the inclination angle of the spin axis to the observer. This is difficult to determine from radio measurements, but high-resolution X-ray measurements from Chandra detailing torus and jet structures have been used to infer the geometry of some pulsars [13]. In most cases, the pulsar distance and age are difficult to determine. Only a couple pulsars can be dated by historical observations of the associated supernova explosion. The distance is often obscured by other emission occurring between the Earth and the pulsar. Lack of knowledge of the age and distance cause substantial uncertainties in the intrinsic luminosity, the surface magnetic field of the neutron star, and the efficiency of converting the rotational energy into high energy emission.

The rotational energy of the neutron star is converted into a relativistic wind of electrons and positrons [14]. This outflow creates an expanding nebula around the pulsar. At the point where the wind is confined by the medium left behind the supernova blast wave, it forms a thin shell of shocked material. Electrons, positrons, and possibly nuclei are accelerated in the shock region and will produce an unpulsed emission component. Whereas the pulsed emission is compact and originates close to the neutron star, the unpulsed component is generated along the surface of an expanding pulsar wind nebula (PWN) and will appear extended for a sufficiently nearby pulsar. The radio signal from some nebulae extends to as much as 0.5°.

PWNe have a rich life cycle related to both the evolution of the pulsar and the supernova remnant. The evolution of PWNe is described by Gaensler & Slane [11] and is presented briefly to highlight a few key features apparent in different energy bands and their connection to the underlying physical processes at work in the nebula.

Following the birth of the pulsar, the wind nebula first forms and begins to expand into the surrounding medium. The cartoon shown in Figure 1 illustrates the structural organization of the remnant. The magnetic field generated by the neutron star is present in the nebula and energetic electrons will undergo synchrotron emission. This appears as a nicely centered, relatively symmetric radio and X-ray nebula, as shown in Figure 1. Over time the magnetic field decreases as the nebula expands. As the cooling of electrons by synchrotron emission becomes less efficient, a population collects at energies suitable for inverse Compton scattering of CMB or other photons in the nebula to gamma-ray energies. At this point, a gamma-ray nebula made up of photons inverse Compton scattered by the electron population can form.

After a few thousand years, a reverse shock from the expanding supernova blast wave can propagate far enough back into the center of the remnant to interact with the expanding PWN. If the medium surrounding the supernova is inhomogeneous, then the reverse shock will propagate at different speeds and arrive non-uniformly at the boundary of the nebula. Because the massive stars that can produce this type of remnant are commonly found in highly populated regions of the galaxy, nonuniform densities are likely. The interaction of the reverse shock with the pulsar wind nebula disrupts it. While the interaction of the reverse shock is taking place, the nebula

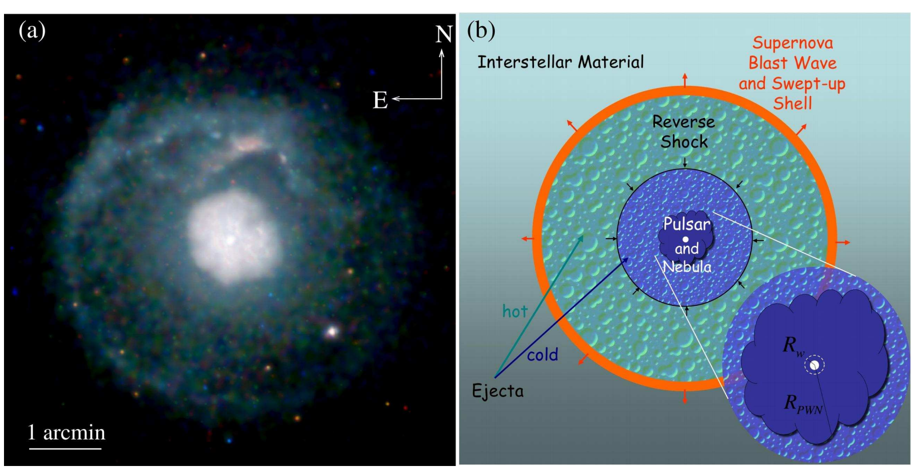

Figure 1: Figure from Gaensler & Slane [11] showing the X-ray image for an unevolved PWN in a) and a cartoon of the general remnant structure in b).

will appear asymmetric and possibly displaced from the position of the pulsar that generated it [9]. The displacement may be amplified by the proper motion of the pulsar, which may be moving away from the origin of the nebula at high speed. An additional enhancement of this phenomena occurs because of the energy dependence of the synchrotron lifetime of the accelerated electron population in the nebula. A critical energy, E_c, depending on the magnetic field strength in the emission zone can be calculated such that electrons with $E > E_c$, cool quickly while lower energy electrons cool more slowly. If the value E_c falls below the energy of electrons emitting synchrotron photons at X-ray frequencies and above the energy of electrons emitting at radio frequencies, then there will be a relic symmetric nebula in the radio band and an asymmetric nebula in the X-ray band for some period of time. The X-ray emission will match the current state of the system more closely and show the disruption, while the radio nebula will reflect the older undisturbed electron distribution. This effective time integration of conditions in the nebula for emission from electrons below the cooling break appears as an energy dependence in the extent of some nebulae.

As the pulsar moves outside the original nebula and into the supernova ejecta, it generates a new and smaller wind nebula. As it progresses toward the edge of the supernova remnant, where the material density drops, its velocity becomes supersonic. At this stage the pulsar is now relatively old, $> 2 \times 10^4$ yr, and the PWN appears as a bow-shock nebula in the radio and X-ray bands.

Recent X-ray missions have detected PWNe associated with pulsars in different stages of development. Bright, symmetric X-ray nebulae have been found associated with young, strong radio pulsars. Asymmetric X-ray nebula have been observed near middle-aged pulsars. Cometary nebulae have been found around older isolated pulsars. Some of the X-ray nebulae have not produced a detection of pulsed emission at radio energies despite good localization and deep searches, suggesting that best knowledge we may get of some pulsars will be that inferred from the X-ray and gamma-ray observations.

PWNe have been found to have detailed X-ray structure. The high-resolution spatial studies possible with Chandra provide valuable information about the pulsar geometry and the nebula structure. The detailed morphology in the X-ray images can be used to study the wind interaction, jet structures, and more fundamentally, they allow the best constraints on the age, size, and distance of the nebula and give some idea of the material density of the surrounding environment. This is largely because at lower frequencies, backgrounds in the galaxy from thermal emission often introduce large errors in estimates of the distance and therefore the size. Accurate knowledge of these is important for properly associating a pulsar with a particular remnant and determining the energetics of the pulsar and the supernova. Several well-studied PWNe still have outstanding questions about acceleration efficiency and luminosity due to uncertainties and the age and distance that prevent definitive statements about the initial rotation period of the pulsar and how rapidly the nebula has expanded.

2.2 Very High Energy PWNe

Perhaps the most intriguing aspect of PWNe is the sudden dominance they have attained as a source class detected by ground-based gamma-ray telescopes, which are sensitive in the very-high energy (VHE) band, $E > 100 GeV$.

At this energy, the emission is thought to arise primarily from inverse Compton scattering of photons from the cosmic microwave background, the interstellar radiation fields, and in some cases the synchrotron photons generated in the nebula. The VHE emission arises from the same electron population that emits synchrotron photons at lower energies. The spectrum of the synchrotron emission depends strongly on the magnetic field strength in the nebula. Emission models for a PWN depend on matching the observed spectrum with that expected from an underlying electron population and thereby restricting the physical parameters of the pulsar and surrounding environment to those that can explain the required electron spectrum. Portions of the synchrotron spectrum, for example, in the infrared band are difficult to measure directly due to strong galactic foregrounds and backgrounds. However, inverse Compton photons at high energies are scattered by the same underlying electron population that is generating the infrared synchrotron emission. The very high energy measurements therefore provide a means of assessing the accelerated electron spectrum in some PWNe at energies that can not be probed by other methods.

The EGRET mission found a large number of unidentified sources, many of which are suspected to be pulsars and PWNe. This conjecture has been strengthened by the discovery of several PWN in the vicinity of the EGRET detections [12, 15].

A survey of regions of the galactic plane in the Southern Hemisphere [4] by H.E.S.S., an atmospheric Cerenkov telescope array, has revealed multiple extended VHE sources associated with pulsars and PWNe [5, 6, 3, 7] These include detections of both young and middle-aged PWNe, the resolution of a jet structure in one, the detection of a spectral maximum in another, and several detections of displaced nebulae. Additional VHE PWNe are likely to be discovered by the current generation of ground-based telescopes. This is suggested by both the existing VHE detections of unidentified extended sources in the galactic plane that are near to unidentified EGRET sources, and the pending completion of new atmospheric Cerenkov arrays that will make more sensitive observations in the Northern Hemisphere.

The most sensitive VHE surveys have been limited in exposure and devoted to regions of the galactic plane. However, there is an expectation that some number of middle-aged pulsars, which are frequently located further from the galactic plane, should be visible at high energies. The limited fields of view (3.5° to 5° in diameter) and operating time (800 hr per year) of atmospheric Cerenkov telescopes means that TeV observations of off-plane PWNe are unlikely without compelling potential targets. There are several large field-of-view VHE instruments operating, but these are at sensitivities below the flux expected from most PWNe at these energies. Even so, results from the all-sky surveys made by by these instruments are quite encouraging. The Milagro experiment sees a broad excess of gamma rays from the Cygnus region of the galaxy [16], which lies in the Northern Hemisphere. This part of the galaxy has not yet been surveyed by the current Northern Hemisphere gamma-ray telescopes, VERITAS and MAGIC, which are beginning array operations in the coming year. In particular, the Milagro survey detects a bright extended source at a position that overlaps with the error regions for two unidentified sources from the 3rd EGRET catalog. One of

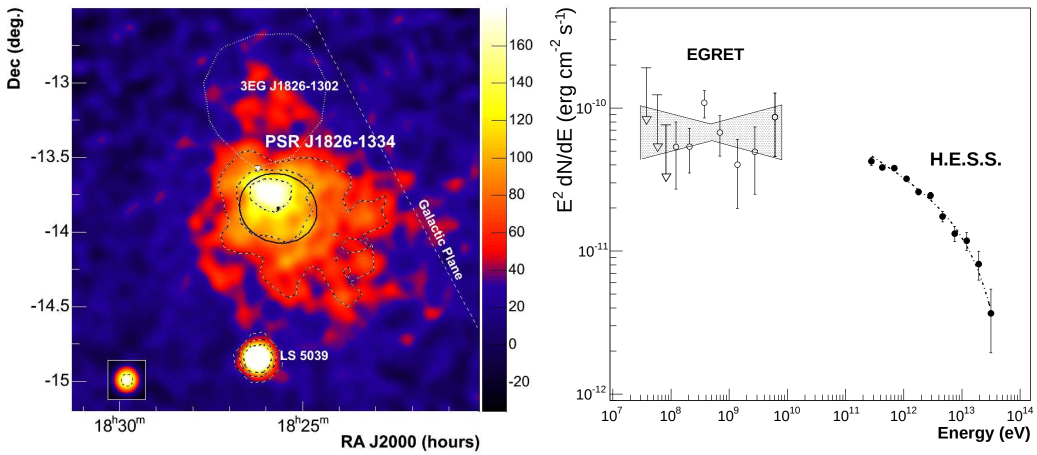

Figure 2: The left-hand figure taken from Aharonian et al. [7] shows a smoothed excess map for a TeV source coincident with an X-ray PWN. The TeV emission is significantly offset from the likely associated pulsar position, shown by a white triangle. The angular resolution for the instrument is indicated at the bottom left. The white contour marks the error region for a nearby unidentified EGRET source. A TeV point source, the microquasar LS 5039, happens to be visible in the same field. The right-hand figure shows the energy flux from H.E.S.S. with that from the possibly associated EGRET source.

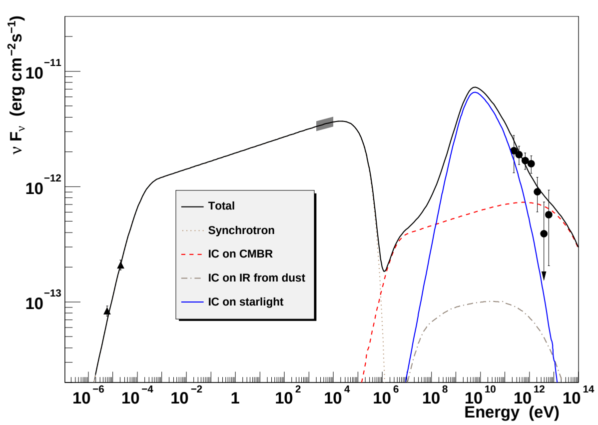

Figure 3: The broadband spectrum for G18.0+0.1 from Aharonian et al. [2] shows a model fit and the predictions for contributions from several source photon populations. This highlights the region of the spectrum where the peak is expected and emphasizes the impact that GLAST detections of PWNe will have.

these is spatially coincident with a recently identified PWN and newly discovered radio pulsar [15]. In a different part of this region of the galaxy, a previous generation atmospheric Cerenkov telescope array, HEGRA, detected a still unidentified extended source, TeV J2032+4130 [1]. Although more recent measurements have not found a pulsar at this location, it is a region known for star formation, and it is possible that this source could be a radio-quiet PWNe.

Summarizing the science results that can be obtained from GeV and related multiwavelength observations of PWNe:

- The luminosity of the PWN, particularly at GeV-TeV energies, can be used to extract the magnetic field strength of the neutron star and nebula.
- High resolution X-ray observations are the best means of identifying pulsar wind nebulae and in some cases provide some knowledge of the pulsar properties when the radio signal is undetectable.
- Measurements of the PWN flux and extent as a function of energy probe the evolution of the remnant.
- Spectral measurements in the GeV range determine the maximum electron energy, which for pulsars with known properties constrains the particle acceleration mechanism.
- Spectral measurements at GeV-TeV energies in combination with the broadband spectrum constrain the photon populations present in the nebula.

3 Background and Relevance to Previous Work

My graduate thesis, *A Search for TeV Emission from Active Galaxies using the Milagro Observatory*, included a time series analysis of several years of Milagro data that was used to constrain spectral models of inverse Compton emission produced in the relativistic jets of active galaxies. This gave me the opportunity to develop a general understanding of particle acceleration in astrophysical sources and a familiarity with the details of nonthermal emission models. It provided me with invaluable experience in data analysis for a large field-of-view instrument. I did extensive work on understanding the dependencies of the sensitivity of the Milagro instrument on energy, throughout the $\sim 2\ sr$ field of view, and in the context of the specific properties of blazars.

I am currently part of the VERITAS collaboration. In the last two years, I have played a key role in the completion and commissioning of the array and participated in the development of the scientific observation plan. I am actively involved in the supernova remnant (SNR) working group and recently developed a proposal for key science measurements that can be made with VERITAS using PWNe. This is part of a larger proposal from the supernova remnant working group to the collaboration for a key science project in the first two years of operations. The SNR project will pursue measurements that will elucidate particle acceleration mechanisms. An involvement with GLAST would not alter my ability to participate in the SNR working group and to submit VERITAS observation proposals. Additionally, I will be able to apply detailed knowledge of the observation capabilities and analysis methodology of the atmospheric Cerenkov telescopes to bringing insight into the effective selection of multiwavelength targets. Having worked on both Milagro and VERITAS, I am in a position to provide an important overlap with the ground-based instruments that will enhance the science done with GLAST.

4 Methodology and Procedure

4.1 Selection of GLAST Sources for Multiwavelength Observations

One of the key scientific objectives of the GLAST mission is "to understand the mechanisms of particle acceleration in AGNs, pulsars, and SNRs." An emerging and vital component of understanding the energy extraction process occurring in pulsars, the evolution of this process over time, and the interaction of the pulsar with the surrounding supernova remnant will come from multiwavelength studies of PWNe at high energies. The pulsar and PWNe science done with GLAST will be quite broad. I am proposing specifically to determine criteria to select PWNe candidates for multiwavelength study. The best candidates are those objects that provide rich science as well as possessing properties that make them good targets for the TeV and X-ray wavebands. How this will work with GLAST is two-fold: one element involves searches in the GLAST data for candidate PWNe from the EGRET and TeV catalogs, as well as looking for counterparts of known X-ray PWNe; the second, requires selecting from the early GLAST source catalog, which is predicted to be copious, the best PWN candidates for observations by TeV, X-ray, and in some cases radio instruments.

4.2 Identification Issues for GLAST Sources

There will be some uncertainty about the identification of GLAST sources and simply narrowing a target list to objects likely to be PWNe will be a significant task. An added component of the multiwavelength observations will be procuring additional information to assist in GLAST source identification. Both the X-ray and TeV instruments have higher angular resolution. X-ray observations will be necessary to provide the localization necessary for deep radio searches for associated pulsars and are the key indicator for pulsar wind nebula identification. However, associations with well-localized TeV observations may be the most useful for making strong identifications with sources at other wavelengths.

Source localization will be critical due to the number of sources GLAST will be sensitive to within the Galaxy. PWNe are expected in star-forming regions, which have a higher background level and increased number of potential gamma-ray emitters. Detections within star forming regions of the galaxy will be suggestive of potential PWNe. Additional criteria may be applied to highlight the most promising candidates. Several key indicators are the size of a source, the steadiness of the emission, and the expectation that the spectrum for PWNe should be harder than that expected from most extragalactic sources. There are suggestions that the nebula emission may have some variability on week to month timescales and this needs to be further explored Detailed criteria will be developed through studies of the expected response of the GLAST instrument to sources based on the current X-ray and TeV observations of PWNe.

4.3 Necessity of a High Energy Analysis

One aspect of the candidate selection that will require specific work is the need for good source localization and the resulting requirement for developing a high energy analysis. GLAST is expected to be able to localize sources with an accuracy < 0.4 arcminutes and the point spread function is expected to be $\sim 0.1^{\circ}$ at 10 GeV as compared to $\sim 3.4^{\circ}$ at 100 MeV. The development of an analysis focused specifically on the highest energy photons will be critical in order to take advantage of the best angular resolution of the instrument and thereby, allow the most convincing positional coincidences to be found. An analysis focused on deriving the best resolution will also help to resolve source confusion in denser galactic regions. Such an analysis can also be used to best define the extent of the nebula at GeV energies and probe the age and evolution history. In the case of highly extended nebulae, there is some potential for the detection of spatial features. The TeV detections show that some nebula extend to $> 0.5\,\mathrm{deg}$ and there has been some success at morphological studies to characterize the VHE brightness and spectrum across the nebula [7]. Additionally, the highest energy photons detected by GLAST will be on the order of 100 GeV and near the lower energies accessible to the ground-based gamma-ray telescopes.

5 Expected Results and Their Application

My expectation is that the timing, position, and spectral properties of the GLAST sources can be used to select a short list of the most promising PWNe candidates both in terms of source identification and probing the PWN emission mechanisms. Detections of pulsed emission will very clearly expose gamma-ray pulsars that may or may not have a detectable nebula. Some GLAST detections will be positionally coincident with well-known TeV and X-ray nebulae and radio pulsars. Matching the timing and spectral information with the expected source properties in the other wavebands, particularly in X-rays, will be important for a strong identification. The identified candidates will be prioritized based on existing information. Some of these sources already have detailed models available and in these cases, it will be important to fill gaps in the spectral emission to best characterize the accelerated particle population. Although PWN emission is generally expected to be dominated by accelerated electrons and positrons, a hadronic contribution has not been ruled out and is still a remaining question. Detailed broadband high energy spectra for PWN in well understood environments will clarify the amount of hadronic contribution that may be present.

A very specific goal will be finding PWNe that can be used to constrain the location of an inverse Compton peak in the spectrum. Knowledge of the peak provides measurements of the maximum electron energy that strongly constrain the acceleration mechanism. Even multiwavelength studies that only include GeV and TeV spectral information will allow measurements of a high energy cutoff in the spectrum, which will probe the PWN environment. Such candidates will reveal the relative dominance of inverse Compton scattering of CMB compared to synchrotron self-Compton and scattering of interstellar backgrounds. In those cases where the peak and a cutoff are observed and the pulsar parameters can be determined from X-ray and radio measurements, severe restrictions will be imposed on the type of model and the pulsar and nebula parameters that could produce the emission. The application of thorough multiwavelength coverage to several clearly identified PWN candidates with good spectral information and perhaps even well-resolved gamma-ray pulse profiles or detailed VHE morphology will greatly advance the understanding of acceleration by the pulsar and nebula, the cooling processes occurring in the nebula over time, and the photon populations contributing to the high energy portion of the spectrum.

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