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Observations of Pulsar Wind Nebulae with the VERITAS Array of Imaging Atmospheric Cherenkov Telescopes

A. KONOPELKO[1], FOR THE VERITAS COLLABORATION[2]
[1]*Purdue University, Department of Physics, 525 Northwestern Avenue, West Lafayette, IN 47907-2036,*
[2]*For full author list see G. Maier, "VERITAS: Status and Latest Results", these proceedings*
akonopel@purdue.edu

Abstract: Many of the recently discovered galactic very high-energy (VHE) γ-ray sources are associated with Pulsar Wind Nebulae, which is the most populous Galactic source category at TeV energies. The extended synchrotron nebulae of these objects observed in the X-ray band are a hallmark of the relativistic winds, generated by the young, energetic neutron stars, that interact with the matter ejected by the supernova explosion and the surrounding interstellar gas. Relativistic electrons, or protons, accelerated in the pulsar winds, or at their shock boundaries, interact with the magnetic field and low energy seed photons to produce the observed VHE γ-ray emission. The VERITAS array of four imaging atmospheric Cherenkov telescopes was designed to study astrophysical sources of γ rays in the energy domain from about 100 GeV up to several tens of TeV. The sensitivity of the VERITAS array allows detailed studies of the morphology and spectral features of γ-ray emission from PWNe. Three northern sky PWNe, G75.2+0.1, G106.6+2.9, and 3C58, were observed with VERITAS during 2006. No evidence for TeV γ-ray emission at the position of the pulsar associated with these PWNe is demonstrated.

Introduction

Charged particles accelerated in the vicinity of a rapidly rotating neutron star, or pulsar, flow out into the interstellar medium and encounter the supernova ejecta from the pulsar's birth event and form a shock. The shock may further enhance the acceleration of the particles which can then attain relativistic speeds. This interaction between the accelerated charged particles and the surrounding medium produces a pulsar wind nebula (PWN). PWNe are often observable at wavelengths from the radio through the γ-ray. Around the youngest, most energetic pulsars, the radio emitting regions of these nebulae are rather amorphous, whereas the X-ray emitting regions can be highly structured [1]. The high spatial resolution of the *Chandra* X-ray Observatory has made it possible to resolve the structures of PWNe. The presence of a PWN can also be inferred spectrally. For instance, a non-thermal component is often seen in the ASCA and INTEGRAL observations of pulsars, such as PSR B1509-58 and PSR B1046-58. This seems to suggest that PWNe are a common phenomenon for all energetic pulsars [2].

It was widely believed that PWNe are potential sources of VHE γ-ray emission. The emission probably arises from inverse Compton (IC) scattering of low-energy photons by the relativistic electrons, while the X-ray emission is associated with the synchrotron radiation from the same population of electrons. The best example of a PWN is the Crab Nebula, which is an established source of pulsed γ-ray emission up to a few GeV detected by EGRET, as well as a source of steady TeV γ rays observed by a number of ground-based Cherenkov detectors and recently with the VERITAS array of four imaging atmospheric Cherenkov telescopes [3]. The TeV emission is thought to originate at the base of its PWN. The H.E.S.S. detector, located in the southern hemisphere, discovered a number of previously unknown γ-ray sources in the VHE domain above 100 GeV. A total of five of these new sources (PSR B1509-58, Vela X, "Kookaburra", SNR G0.9+0.1, PSR B1823-13) are apparently associated with PWNe. Such associations rest on a positional and morphological match of the VHE γ-ray source to a known PWN at lower energies. It is worth noting that in all cases the pulsar is sig-

Pulsar	PWN	P (ms)	B (10^{12}G)	t (kyr)	$\dot{\mathrm{E}}$ (10^{36}erg/s)	d (kpc)	F_γ(10^{-11}erg/s)
J2021+3651	G75.2+0.1	104	3.2	17	3.4	12	7
J2229+6114	G106.6+2.9	51.6	2	10.5	22	3	4
J0205+6449	3C58	65	3.6	5	27	3.2	0.8

Table 1: Physical parameters of observed pulsars and their PWNe.

nificantly offset from the center of the VHE γ-ray source. This offset could be attributed to the interaction between the PWN and the SNR ejecta [4].

A detailed survey of the inner part of the Galactic Plane at VHE γ-ray energies has been carried out with H.E.S.S. Fourteen previously unknown, extended sources were detected with high significance [5]. Some of these sources have fairly well-established counterparts at longer wavelengths, based exclusively on positional coincidence, but others have none at all. A number of models have been proposed regarding the nature of these unidentified VHE γ-ray sources. At present, PWNe and shell-type SNRs are considered the most plausible counterparts for the remaining unidentified VHE γ-ray sources amongst the numerous possibilities that have been put forward.

Targets

Motivated by the growing catalog of TeV PWNe, VERITAS, in 2006, observed three northern sky PWNe, G75.2+0.1, G106.6+2.9, and 3C58, associated with young, energetic pulsars (see Table 1).

PSR J2021+3651. A *Chandra* observation showed this pulsar to be embedded in a compact, bright X-ray PWN (PWN G75.2+0.1) with the standard torus and jet morphology [6]. Its X-ray spectrum is well fit by a power-law model with photon index Γ=1.7 and a corresponding 0.3-10 keV flux of $1.9{\times}10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. This young Vela-like pulsar is coincident with the EGRET γ-ray source GeV 2020+3651. Recently, the Milagro γ-ray observatory detected an extended source or multiple unresolved sources of γ rays at a median-detected energy of 12 TeV [7] coincident with the same region. The radio dispersion measure suggests a distance to PWN G75.2+0.1 $\mathrm{d} \geq 10$ kpc, but this measurement could have been contaminated by the gas in the Cygnus region and the true distance may be in fact substantially closer. Presently PWN G75.2+0.1 is considered to be one of the best candidates for the Milagro source (MGRO J2021+37) and it is likely to be seen in the energy range covered by VERITAS.

PSR J2229+6114. The *Chandra* X-ray image of PWN G106.6+2.9 shows an incomplete elliptical arc and a possible jet, similar to the Vela PWN [8]. PSR J2229+6114 is a compelling counterpart of the EGRET source 3EG J2227+6122. This young, energetic pulsar is second only to the Crab pulsar in spin-down power, and it is substantially more luminous than the Vela pulsar. Given the relatively small distance of 3 kpc this pulsar has a very high rank among all pulsars in the discriminant $\dot{E}/d^2$. Part of this flux can be converted into a high flux of VHE γ rays.

3C58. 3C58 is a young Crab-like SNR generally accepted as being the remnant of the historical supernova SN 1181. A compact object (nebula) at the center of the SNR has been resolved in *Chandra* X-ray data [9], and is centered on PSR J0205+6449. Given its very high spin-down power, the pulsar is capable of supplying the energy of the X-ray nebula, $L_x = 2.9 \times 10^{34}\,\mathrm{ergs\,s^{-1}}$, and may have substantial VHE γ-ray emission.

The TeV γ-ray fluxes expected from the PWNe around both PSR J2021+3651 and PSR J2229+6114 in terms of a hadronic-leptonic model for the high-energy processes inside the PWNe [10] exceed 10% of the Crab Nebula flux above 200 GeV (see Table 1). This suggests that both PSR J2021+3651 and PSR J2229+6114 should be detectable with VERITAS after rather short exposures. A somewhat lower γ-ray flux of a few percent of the Crab Nebula was predicted for 3C58 [10], however it is still well above the sensitivity limit of the VERITAS detector for a reasonable exposure.

VERITAS Observations and Analysis

VERITAS is an array of four imaging Cherenkov telescopes sited in Amado, Arizona, and dedicated to the detection of VHE γ rays with energies above 100 GeV. Each telescope has a tessellated mirror

Pulsar	$N_{\rm tel}$	$N_{\rm runs}$	R (Hz)	T (hr)	Θ (°)	On	Off	$\alpha_{Li\&Ma}$	S/N (σ)	U.L. (Crab)
J2021+3651	2	23	100	8.4	30.5	189	512	0.33	1.19	4.6%
J2229+6114	2	32	88	12	31.8	151	543	0.25	0.19	2.7%
J0205+6449	3	17	147	5.3	34.2	109	406	0.25	0.32	2.4%

Table 2: Summary of data.

with an area of $\simeq 110$ m^2 and a camera consisting of 499 photomultiplier tubes. The first telescope in the array has been operating since February 2005. First stereo observations with two telescopes began in April 2006, and the full array of four telescopes has been operational since January 2007. A full VERITAS array has the sensitivity of 7 mCrab (5σ detection over 50 hour exposure). The angular resolution of better than $0.14°$ and a 3.5° field of view enable VERITAS to detect and study a variety of compact galactic γ-ray sources like PWNe.

The VERITAS observations of three PWNe were made while the system was under construction. Observations of PSR J2021+3651 and PSR J2229+6114 in November 2006 were made with a two telescope system. Later a third telescope was added to the system and observations of 3C58 in December 2006 were made with three telescopes. The data were taken mostly in 20 minute runs with a few runs of 28 minutes using the *wobble* mode. In this mode, the source direction is positioned $\pm 0.3°$ (a $\pm 0.5°$ offset was used for later observations) in declination or right ascension relative to the center of the camera field of view. The sign of the offset was altered in successive runs to reduce systematic effects. The *wobble* mode allows on-source observation and simultaneous estimation of the background induced by charge cosmic-ray particles. This eliminates the need for off-source observations and consequently doubles the amount of available on-source time.

For final analysis only those runs passing the data quality criteria are used. The images are calibrated and then cleaned using a two-threshold picture/boundary selection procedure which requires a pixel to have a signal greater than 5.0 pedestal variances (PV) and a neighboring pixel to have a signal larger than 2.5 PV. The pixels with a signal greater than 2.5 PV are included only if they have a neighbor with a signal greater than 5.0 PV. After image cleaning the shower images are parameterized using a standard second-moment approach. The shower geometry is reconstructed using stereoscopic techniques with a typical angular resolution of about 0.14° and an average accuracy of better than 20 m in the determination of the shower core location. To ensure that images are not truncated by the camera edge, only images with the center of gravity less than 1.3° from the center of the camera are used in the reconstruction. In addition, at least two images are each required to exceed a minimum total signal of 400 digital counts of the respective flash analog-to-digital converter to ensure that the showers are well reconstructed.

After the shower reconstruction, the cosmic-ray background events are rejected using standard cuts on mean scaled width and mean scaled length parameters. The number of events passing cuts in a circle of standard angular size around the source position gives the number of on-source (On) counts. The background is estimated using all events passing cuts in a number of non-overlapping circles of the same size. The centers of these circles are positioned at the wobble offset from the tracking position. The number of background regions may vary depending on the actual wobble offset used in the observation. The use of a larger background region reduces the relative statistical error on the background measurement. For a given number of on-source and background counts acquired after event selection the significance of the excess is calculated following the method of Equation (17) in the Li & Ma technique [11]. It is worth noting that the data have been analyzed using independent analysis packages (see [12, 13] for details on the analyses). All of these analyses yield consistent results.

Results and Conclusion

Table 2 summarizes the results of the VERITAS observations of each of the individual sources. These objects have been observed with VERITAS for rather limited exposure times. The longest exposure (T) of 12 hrs was for PSR J2229+6114. All observations were made at the median zenith angle (Θ) of $\sim 30°$. Parameter $\alpha_{Li\&Ma}$ used in the Li & Ma technique is also given in Table 2. No significant excess suggesting TeV γ-ray emission is evident for any of the observed PWN. The 99% confidence level flux upper limits [14] at the pulsar position expressed in the flux of the Crab Nebula are shown in Table 2.

Present VERITAS upper limits for a sample of northern PWNe contradict predictions of high VHE γ-ray fluxes made in [10], which might possibly constrain the choice of magnetic field strength within the nebulae. For PSR J2021+3651 a very hard γ-ray spectrum of hadronic origin with a peak at $\sim$10 TeV, which is the median-energy of the MILAGRO detection, and sharp fall off at higher energies as suggested in [15] would still satisfy the VERITAS upper limit. A similar spectrum has been observed from PWN Vela X by H.E.S.S. [16]. Note, however, that present VERITAS upper limits were derived assuming a point like γ-ray source. Estimating the VERITAS upper limit for an extended source seems to be premature given that the exact localization and angular extent of the VHE γ-ray source detected by the MILAGRO γ-ray observatory are still in the process of final evaluation.

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