Recent VERITAS Results on Galactic Supernova Remnants and Pulsar Wind Nebula

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1 Introduction

Supernova remnants (SNR) and pulsar wind nebulae (PWN) are among the most numerous of TeV-emitting objects in the sky and provide excellent laboratories for the investigation of high-energy particle acceleration in astrophysical environments. In many cases, their relative proximity to earth and resultant large angular sizes allow for detailed mapping of emission regions and precise correlations to emission at other wavelengths.

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) Observatory maintains an active program of SNR/PWN observations which proceeds along two channels: unbiased sky survey and individual targeted observations. Each of these programs has led to the detection and, indeed, discovery of Galactic gamma-ray emitting objects. In the following, we report on some of the highlights of our observing program from the first three years of observations, including the recent detection of faint TeV gamma-ray emission from the direction of Tycho's supernova remnant (G120.1+1.4).

2 VERITAS Observatory

VERITAS is an array of four 12m-diameter imaging atmospheric Cherenkov telescopes (IACTs) located at the Fred Lawrence Whipple Observatory in southern Arizona. Designed to measure photons in the energy range of 100 GeV to 30 TeV with a typical energy resolution of 15-20%, VERITAS features an angular resolution of $r_{68\%} \sim 0.1^{\circ}$ over a 3.5° field-of-view.

VERITAS began full operations in autumn 2007 and has, to date, detected 30 gamma-ray sources in 6 different source classes. The recent relocation of one of the four telescopes has resulted in an improved point source sensitivity of 1% of the Crab Nebula flux in under 30 h [5σ, 70° elevation]. For more details on the the telescopes or their operation, see [1] or [2]. A recent review of the atmospheric Cherenkov technique can be found in [3].

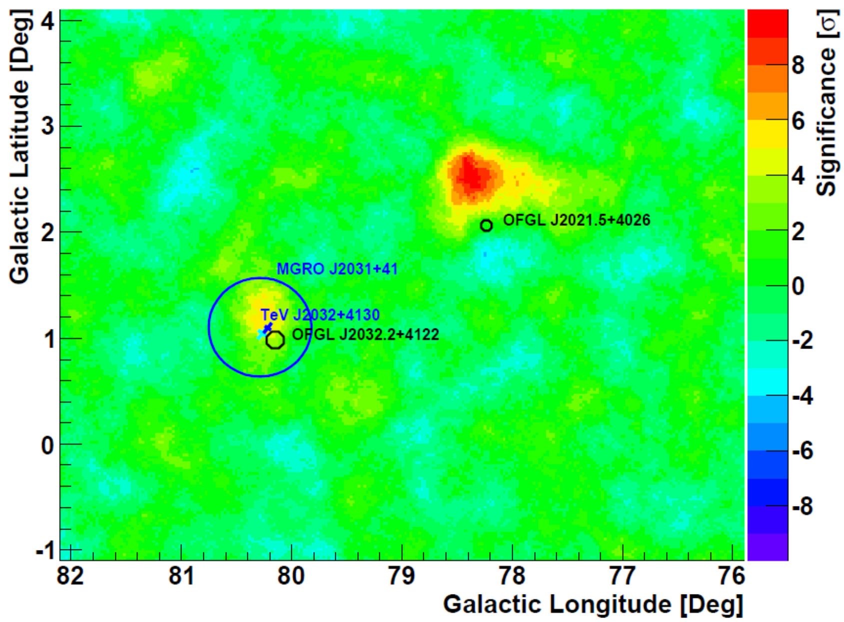

Figure 1: Significance map of a portion of the VERITAS sky survey map (See § 3), including all follow-up data taken through autumn 2009. The error circles of two Fermi/LAT Bright Sources[4], 0FGL J2021.5+4026 and 0FGL J2032.2+4122, are indicated by black circles. The position of TeV J2032+4130 as measured by HEGRA and MAGIC is indicated by the dark and light blue crosses, respectively[5, 6]. The position and extent of MGRO J2031+41[7] is indicated with the blue circle. Figure taken from [8].

3 Sky Survey

The VERITAS sky survey is a deep blind search of the Galactic plane, centered on the "Cygnus Region" between $67^\circ < \ell < 82^\circ$ and $-1^\circ < b < 4^\circ$. The Cygnus Region is a clear choice for such a search, due to its large number of potential TeV gamma-ray sources, including pulsar wind nebulae, supernova remnants, high-mass X-ray binaries, as well as several previously-detected high-energy gamma-ray sources. The survey consisted of 112 base hours of observation, with another 56 hours of follow-up studies. The sensitivity limit of the survey (99% CL) reaches 3% of the Crab Nebula flux for point sources above 200 GeV and 8% for moderately extended sources, above the same energy. For more details, see [8].

Figure 1 shows a significance map produced from a portion of the VERITAS sky survey observations. Two TeV emitters are clearly evident on this map. The first, located near $\ell = 80.3^\circ, b = 1^\circ$, is apparently associated with the well-known weak ($\sim 3\%$ Crab[6]) source TeV J2032+4130, an unidentified object first discovered by the HEGRA Collaboration[5], and spatially coincident with Whipple[9], Milagro[7] and Fermi sources[4].

The second hotspot on the map represents a new TeV source, VER J2019+407. Evidence for emission from this source first appeared in the base survey, and was confirmed by follow-up observations taken in the fall of 2009. Preliminary results indicate the presence of a high-significance (7.5σ) extended source ($\sim 0.2^\circ$) with a flux above 1 TeV of $\sim 3\%$ that of the steady Crab Nebula flux. The peak of the excess emission appears to be centered on the northwestern corner of the SNR γCygni (G78.2+2.1), which is the extended ($\sim 1^\circ$) remnant of a relatively nearby (~ 1.5 kpc) supernova event which took place perhaps 10 kyr ago[10]. A detailed investigation of the possible emission mechanisms is currently underway[11].

4 Targeted Observations

In addition to the sky survey, VERITAS performs traditional targeted observations of likely TeV gamma-ray emitters. Candidates for observation typically exhibit non-thermal radiation at other wavelengths and/or feature other exceptional properties, such as hosting high spindown-power pulsars. Below we discuss some of the highlights of the targeted Galactic observation program from the last three years.

4.1 Cassiopeia A

Cassiopeia A (Cas A) is the young (~ 330 year-old) and well-studied shell-type remnant of a massive star, possibly of the Wolf-Rayet variety[12, 13]. Located 3.4 kpc away, Cas A has an angular diameter of only 5' and is the brightest radio source in the sky, with a synchrotron spectrum which extends all the way up to hard (~ 100 keV) X-rays. The high-energy end of this spectrum has been attributed to the presence of electrons of at least 40 TeV (see, e.g., [14]).

Cas A was first detected in TeV gamma-rays after a 232 hour exposure by HEGRA[15]. This detection was subsequently confirmed by MAGIC in a 47 hr exposure[16]. At GeV energies, EGRET did not detect Cas A, though Fermi/LAT has reported a strong detection consistent with a point source[17].

VERITAS has observed Cas A for 22 hours, resulting in an 8.3σ detection[18]. The source, which has a flux of $\sim 3\%$ that of the Crab Nebula above 200 GeV, shows no strong evidence for extension beyond the VERITAS point spread function, and has an energy spectrum which is describable with a power-law of index $\alpha = 2.61 \pm 0.24_{stat} \pm 0.2_{sys}$. The Fermi/LAT team has modeled the high-energy emission from Cas A and finds that a hadronic emission model with a hard proton population (spectral index $\alpha = 2.1$) and a cutoff energy of 10 TeV fits the combined GeV/TeV excess well.

4.2 IC 443

IC 443 is a large ($\sim$ 45') and well-studied composite SNR likely resulting from the core-collapse death of a massive star some 3-30 kyr years ago (see, e.g., [19]). This remnant, which is generally assumed to be ~ 1.5 kpc distant, stands as one of the better examples of an SNR interacting with a dense molecular cloud. In addition, the southern portion of the remnant contains the PWN CXOU J061705.3+222127, which may or may not be associated with the supernova.

These features make IC 443 an excellent candidate for TeV emission and indeed such emission has been reported by both the MAGIC[20] and VERITAS Collaborations[21]. In 38 hours of observation time, VERITAS has resolved high-significance extended ($\sim 0.16°$) TeV emission coming from the direction of the peak of the molecular cloud density. The $\sim$ 3%-Crab-level emission (above 300 GeV) is consistent with the location of reported OH maser emission (which is considered a signpost of shock/cloud interactions[22]) and, notably, is somewhat displaced from the location of the PWN. The energy spectrum of the TeV emission can be described by a power-law with index $\alpha = 2.99 \pm 0.38_{stat} \pm 0.3_{sys}$.

Recent data from the Fermi/LAT team[23] have confirmed an earlier EGRET detection (3EG J6017+2238)[24] and revealed high-energy (HE; 200 MeV - 50 GeV) gamma-ray emission from an extended region overlapping the TeV detections. As with those detections, the HE emission is centered on a position well offset from the PWN. A neutral pion decay model from the Fermi team which assumes a broken power-law spectrum of parent protons and a significant mass of target material ($10^4 M_\odot$) fits the overall gamma-ray spectrum from 200 MeV to 2 TeV[23]. On the other hand, recent results from the AGILE team[25] describe 0.1-3 GeV emission peaking significantly (0.4°) to the northeast of the VERITAS centroid.

4.3 G54.1+0.3

The SNR G54.1+0.3 is a young ($\sim$ 3 kyr) X-ray PWN which, by virtue of its similarities to that object, has been called a “cousin to the Crab”[26]. Driven by the high-spindown power (1.2×10^{37} erg/s) pulsar, PSR J1930+1852, G54.1+0.3 exhibits a compact ($\sim 2'$) jet+torus morphology and an infrared shell, possibly from dust condensed out of the supernova ejecta[27]. An apparent association with molecular cloud emission at -53 km/s places the remnant at 6.2 kpc[28].

No detections at GeV energies have been reported, and the best TeV limits (20% of

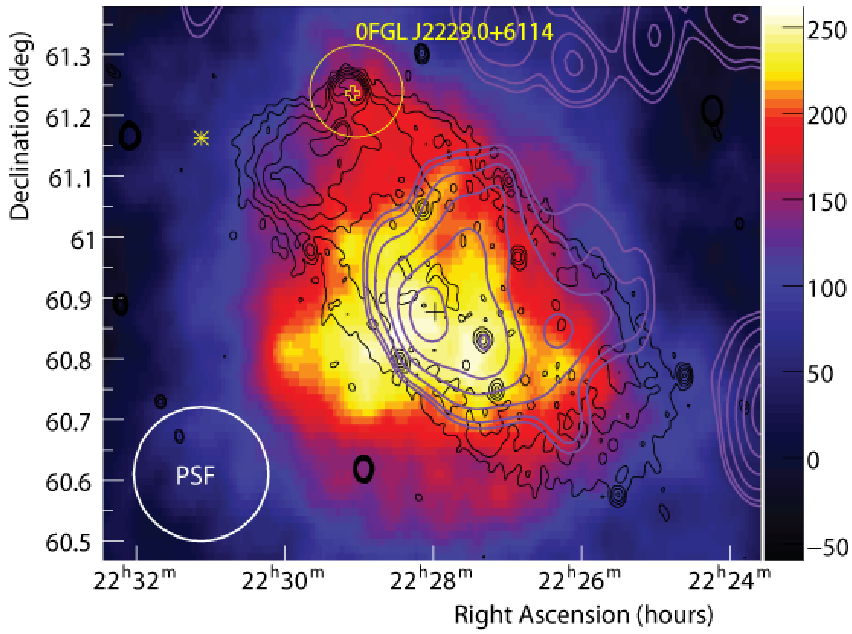

Figure 2: Sky map of TeV gamma-ray emission from G106.3+2.7, as measured by VERITAS. The color scale indicates the number of excess gamma-ray events from the region, using a squared integration radius of 0.08 deg^2. The centroid of the TeV emission is indicated with a thin black cross. Overlaid are 1420 MHz radio contours from the DRAO Synthesis Telescope (thin black lines - [32]) and ^{12}CO emission (J=1-0) from the high-resolution FCRAO Survey, centered on -5 km/s (magenta lines - [33]). The open yellow cross shows the location of pulsar PSR J2229+6114. The yellow circle indicates the 95% error contour for the Fermi source 0FGL J2229.0+6114. The circle labeled PSF represents the VERITAS gamma-ray point-spread function for this analysis (68% containment). Figure taken from [34]

the Crab Nebula flux above 600 GeV) come from the HEGRA collaboration[29]. VERITAS observed G54.1+0.3 for 22 hours in 2008/2009, after 15 hrs of partial-moonlight observations in 2007/2008 revealed a hint of signal. These observations resulted in a 7σ detection of a point-like object, centered on the PWN location. The integral flux of the source above 1 TeV is 2.5% of the Crab Nebula flux, and the energy spectrum follows a power-law with index $2.39 \pm 0.23_{stat} \pm 0.3_{sys}$. The X-ray to TeV gamma-ray luminosity ratio is the lowest among all the PWN thought to be driven by young rotation-powered pulsars, which possibly indicates a particle-dominated PWN, or a substantial contribution of seed photons from the IR photon fields in the dust shell[30, 31].

4.4 G106.3+2.7

G106.3+2.7 is the remnant of a nearby (800 pc) Galactic supernova which occurred approximately 10 kyr years ago[35]. Contained within the body of the remnant is one of the most energetic pulsars in the northern sky, PSR J2229+6114 ($\dot{E} = 2.2 \times 10^{37}$ erg s^{-1}), and its associated PWN, G106.6+2.9. The radio remnant is faint and spans $\sim 0.8^\circ$ by $\sim 0.3^\circ$ degrees on the sky. ^{12}CO emission at -5 km/s overlaps the main bulk of the remnant, somewhat displaced to the southwest from the PWN position (see Figure 2). Apart from the PWN region, the remnant is not well-mapped in X-rays.

At higher energies, bright pulsed GeV emission[4, 36] is reported by the Fermi/LAT team (0FGL J2229.0+6114), coincident with the radio pulsar, and the broadly-extended multi-TeV Milagro source MGRO J2228+61[7] covers both the PWN and much of the remnant. At TeV energies, the tightest limits come from MAGIC, who quote a point source upper limit of 10% of the Crab above 220 GeV, centered on the pulsar position[37].

VERITAS observations of G106.3+2.7, motivated by the pulsar energetics, were made in 2008, resulting in 33 hours of exposure. As shown in Figure 2, these observations resolve high-significance (6.0σ post-trials) TeV gamma-ray emission coming from an extended portion of the radio remnant[34]. Notably, the centroid of the TeV flux, which is $\sim 5\%$ that of the Crab Nebula above 1 TeV, is centered near the peak of the coincident molecular cloud, some 0.4° away from the pulsar position. This may suggest that the emission is due to hadronic interactions between cosmic rays accelerated in the remnant and the material of the cloud. This scenario would be strengthened if the emission reported by Milagro can be firmly associated with the VERITAS source, since the extrapolation of the VERITAS energy spectrum ($\alpha = 2.29 \pm 0.33_{stat} \pm 0.3_{sys}$) passes, without significant curvature, through the data point at ~ 35 TeV reported by Milagro. This combined spectrum would be harder to accommodate in a typical inverse Compton scenario[38].

4.5 Tycho's Supernova Remnant

Tycho's SNR, G120.1+1.4, is the historical shell-type remnant of a Type Ia supernova event which is believed to have been first observed in 1572. Several characteristics make Tycho a natural candidate for gamma-ray observations. Subtending only 8' on the sky (in radio and X-ray), it is nearly a point source for IACTs, and its distance is relatively small, estimated to be between $2.5 - 5.0$ kpc from earth. In addition, X-ray maps of the object show strong non-thermal emission along the SNR rims and reveal thin filamentary structures which have been associated with high-energy electron acceleration[39, 40, 41]. Furthermore, a slowing of the remnant's expansion rate to the east has been associated with the presence of a dense molecular cloud (e.g., [42, 43, 44]). Overall, the mean expansion rate of the remnant suggests a progression into the Sedov phase and a detailed X-ray study of the shock dynamics[40] has inferred the presence of efficient hadronic particle acceleration in the remnant.

Tycho has been observed many times at gamma-ray energies, with no detections yet reported by EGRET, Fermi/LAT, HEGRA, Whipple, or MAGIC. The most constraining upper limits currently come from MAGIC[45], who quote a 3σ point source upper limit of 1.7% of the Crab Nebula flux above 1 TeV at the center of the remnant. VERITAS observations of Tycho spanned the seasons 2008 to 2010. After quality cuts, 67 hours of data remain, at a mean elevation of 52°. These observations reveal TeV emission coming from the direction of Tycho with a pre-trials statistical significance of 5.7σ (see Figure 3). After a conservative set of *a priori* scanning trials which tile the angular region surrounding

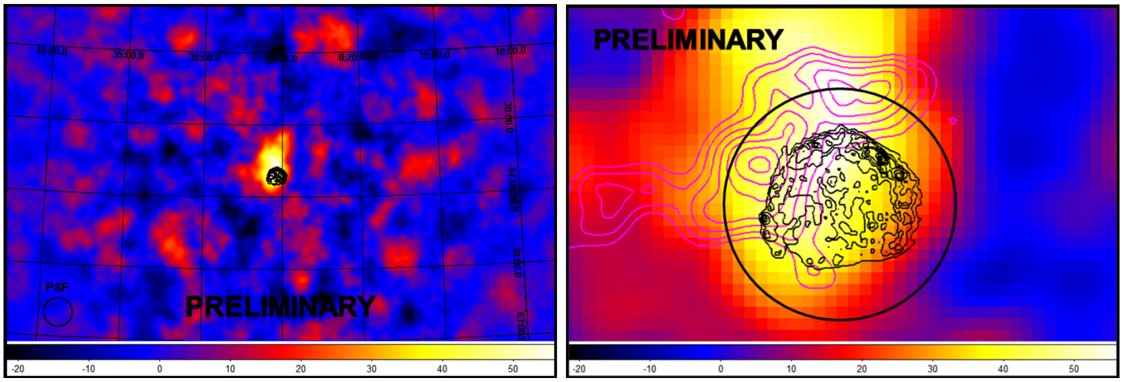

Figure 3: Preliminary VERITAS excess maps of TeV gamma-rays from the direction of Tycho. Left: Wide view of the remnant with superimposed X-ray contours from the Chandra ACIS[40]. Right: Zoomed image of the center of the remnant, again with black contours from the Chandra ACIS. The magenta contours are ^{12}CO data from the FCRAO Survey[33], centered on -64 km/s[43]. On both plots, the color scale shows the (smoothed) excess number of TeV gamma rays and the black circles represent the point spread function of VERITAS for the cuts used.

the remnant, a post-trials significance of 5.0σ is obtained. The emission is weak, at $\sim 1\%$ of the Crab Nebula flux (above 1 TeV) and peaks somewhat to the north of the remnant, overlapping a region with enhanced CO emission. Given the point-spread function of the instrument, there is no strong statistical evidence for extension in the detected emission. Detailed studies of the multiwavelength emission morphology, gamma-ray energy spectrum, and possible emission mechanisms are currently in progress[46].

5 Summary

During its first three years of operation, VERITAS has undertaken a successful program of blind and targeted observations of Galactic supernova remnants and pulsar wind nebulae. This program has resulted in many detections and discoveries (see Table 1) and is contributing, along with observations from HESS, MAGIC, Fermi, AGILE, and Milagro, to a better understanding of the high-energy behavior of these objects. We look forward to the additional insights to be gained from future observations of potential new sources and deeper observations of existing sources.

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Source	Type	Distance (kpc)	Age (kyr)	Integral Flux ($\times 10^{-13}$ cm^{-2} s^{-1})	Flux Energy (GeV)	Ref.
Crab	PWN	2	1.0	$236 \pm 9.7_{stat} \pm 47_{sys}$	1000	[47]
Cas A	SNR	3.4	0.3	$7.8 \pm 1.1_{stat} \pm 1.6_{sys}$	1000	[18]
IC 443	SNR+PWN	1.5	3-30	$46.3 \pm 9.0_{stat} \pm 9.3_{sys}$	300	[21]
G54.1+0.3	PWN	6.2	3.0	$5.4 \pm 0.9_{stat} \pm 1.1_{sys}$	1000	[30]
G106.3+2.7	SNR+PWN	0.8	10	$11.1 \pm 2.5_{stat} \pm 2.8_{sys}$	1000	[34]
VER J2019+407	SNR?	1.5	10	$\sim 7^*$	1000	[8]
Tycho	SNR	2.5-5.0	0.4	$\sim 2^*$	1000	[46]

Table 1: Table of VERITAS detections of supernova remnants and pulsar wind nebulae. Fluxes marked with a * are approximate.

paper has used data from the Canadian Galactic Plane Survey, a Canadian project with international partners, supported by NSERC. We acknowledge the work of the technical support staff at the FLWO and of all the collaborating institutions in the construction and operation of the instrument.

References

[1] T. C.Weekes *et al.*, "VERITAS: the Very Energetic Radiation Imaging Telescope Array System," *Astroparticle Physics*, vol. 17, pp. 221–243, May 2002.

[2] J.Holder *et al.*, "The first VERITAS telescope," *Astroparticle Physics*, vol. 25, pp. 391–401, Jul. 2006.

[3] F.Aharonian *et al.*, "High energy astrophysics with ground-based gamma ray detectors," *Reports on Progress in Physics*, vol. 71, no. 9, pp. 096 901–+, Sep. 2008.

[4] A. A.Abdo *et al.*, "Fermi/Large Area Telescope Bright Gamma-Ray Source List," ApJS, vol. 183, pp. 46–66, Jul. 2009.

[5] F.Aharonian *et al.*, "The unidentified TeV source (TeV J2032+4130) and surrounding field: Final HEGRA IACT-System results," A&A, vol. 431, pp. 197–202, Feb. 2005.

[6] J.Albert *et al.*, "MAGIC Observations of the Unidentified γ-Ray Source TeV J2032+4130," ApJ, vol. 675, pp. L25–L28, Mar. 2008.

[7] A. A.Abdo *et al.*, "TeV Gamma-Ray Sources from a Survey of the Galactic Plane with Milagro," ApJ, vol. 664, pp. L91–L94, Aug. 2007.

[8] A.Weinstein and VERITAS, "The veritas survey of the cygnus region of the galactic plane," in *Proc. 2009 Fermi Symposium*, 2009.

[9] A.Konopelko *et al.*, “Observations of the Unidentified TeV γ-Ray Source TeV J2032+4130 with the Whipple Observatory 10 m Telescope,” ApJ, vol. 658, pp. 1062–1068, Apr. 2007.

[10] Y.Ladouceur and S.Pineault, “New perspectives on the supernova remnant G78.2+2.1,” A&A, vol. 490, pp. 197–211, Oct. 2008.

[11] V.Acciari and VERITAS, *in preparation*, 2010.

[12] R. A.Fesen and R. H.Becker, “New clues to the Cassiopeia A supernova progenitor,” ApJ, vol. 371, pp. 621–625, Apr. 1991.

[13] P. A.Young *et al.*, “Constraints on the Progenitor of Cassiopeia A,” ApJ, vol. 640, pp. 891–900, Apr. 2006.

[14] G. E.Allen *et al.*, “Evidence of X-Ray Synchrotron Emission from Electrons Accelerated to 40 TeV in the Supernova Remnant Cassiopeia A,” ApJ, vol. 487, pp. L97+, Sep. 1997.

[15] F.Aharonian *et al.*, “Evidence for TeV gamma ray emission from Cassiopeia A,” A&A, vol. 370, pp. 112–120, Apr. 2001.

[16] J.Albert *et al.*, “Observation of VHE γ-rays from Cassiopeia A with the MAGIC telescope,” A&A, vol. 474, pp. 937–940, Nov. 2007.

[17] A. A.Abdo *et al.*, “Fermi-Lat Discovery of GeV Gamma-Ray Emission from the Young Supernova Remnant Cassiopeia A,” ApJ, vol. 710, pp. L92–L97, Feb. 2010.

[18] V. A.Acciari *et al.*, “Observations of the Shell-type Supernova Remnant Cassiopeia A at TeV Energies with VERITAS,” ApJ, vol. 714, pp. 163–169, May 2010.

[19] E.Troja *et al.*, “XMM-Newton observations of the supernova remnant IC 443. II. Evidence of stellar ejecta in the inner regions,” A&A, vol. 485, pp. 777–785, Jul. 2008.

[20] J.Albert *et al.*, “Discovery of Very High Energy Gamma Radiation from IC 443 with the MAGIC Telescope,” ApJ, vol. 664, pp. L87–L90, Aug. 2007.

[21] V. A.Acciari *et al.*, “Observation of Extended Very High Energy Emission from the Supernova Remnant IC 443 with VERITAS,” ApJ, vol. 698, pp. L133–L137, Jun. 2009.

[22] M.Wardle and F.Yusef-Zadeh, “Supernova Remnant OH Masers: Signposts of Cosmic Collision,” *Science*, vol. 296, pp. 2350–2354, Jun. 2002.

[23] A. A.Abdo *et al.*, “Observation of Supernova Remnant IC 443 with the Fermi Large Area Telescope,” ApJ, vol. 712, pp. 459–468, Mar. 2010.

[24] R. C.Hartman *et al.*, “The Third EGRET Catalog of High-Energy Gamma-Ray Sources,” ApJS, vol. 123, pp. 79–202, Jul. 1999.

[25] M.Tavani *et al.*, "Direct Evidence for Hadronic Cosmic-Ray Acceleration in the Supernova Remnant IC 443," ApJ, vol. 710, pp. L151–L155, Feb. 2010.

[26] F. J.Lu *et al.*, "Chandra Observation of Supernova Remnant G54.1+0.3: A Close Cousin of the Crab Nebula," ApJ, vol. 568, pp. L49–L52, Mar. 2002.

[27] T.Temim *et al.*, "Deep Chandra Observations of the Crab-like Pulsar Wind Nebula G54.1+0.3 and Spitzer Spectroscopy of the Associated Infrared Shell," ApJ, vol. 710, pp. 309–324, Feb. 2010.

[28] D. A.Leahy *et al.*, "Distance Determination to the Crab-Like Pulsar Wind Nebula G54.1+0.3 and the Search for its Supernova Remnant Shell," AJ, vol. 136, pp. 1477–1481, Oct. 2008.

[29] F. A.Aharonian *et al.*, "A search for TeV gamma-ray emission from SNRs, pulsars and unidentified GeV sources in the Galactic plane in the longitude range between -2 deg and 85 deg." A&A, vol. 395, pp. 803–811, Dec. 2002.

[30] V. A.Acciari *et al.*, "Discovery of VHE γ-ray emission from the SNR G54.1+0.3," *ArXiv e-prints 1005.0032*, Apr. 2010.

[31] R. A.Chevalier, "Pulsar wind nebulae: theoretical aspects and observational constraints," *Advances in Space Research*, vol. 33, pp. 456–460, 2004.

[32] T. L.Landecker *et al.*, "The synthesis telescope at the Dominion Radio Astrophysical Observatory," A&AS, vol. 145, pp. 509–524, Sep. 2000.

[33] M. H.Heyer *et al.*, "The Five College Radio Astronomy Observatory CO Survey of the Outer Galaxy," ApJS, vol. 115, pp. 241–+, Apr. 1998.

[34] V. A.Acciari *et al.*, "Detection of Extended VHE Gamma Ray Emission from G106.3+2.7 with Veritas," ApJ, vol. 703, pp. L6–L9, Sep. 2009.

[35] R.Kothes *et al.*, "The Supernova Remnant G106.3+2.7 and Its Pulsar-Wind Nebula: Relics of Triggered Star Formation in a Complex Environment," ApJ, vol. 560, pp. 236–243, Oct. 2001.

[36] A. A.Abdo *et al.*, "Fermi Large Area Telescope Detection of Pulsed γ-rays from the Vela-like Pulsars PSR J1048-5832 and PSR J2229+6114," ApJ, vol. 706, pp. 1331–1340, Dec. 2009.

[37] E.Aliu, "Vhe gamma-ray observations of northern sky pulsar wind nebulae with the magic telescope," Ph.D. dissertation, Universitat Autonoma de Barcelona, October 2007.

[38] O. C.de Jager and A.Djannati-Ataï, "Implications of H.E.S.S. observations of pulsar wind nebulae," *ArXiv e-prints 0803.0116*, Mar. 2008.

[39] A.Bamba *et al.*, “A Spatial and Spectral Study of Nonthermal Filaments in Historical Supernova Remnants: Observational Results with Chandra,” ApJ, vol. 621, pp. 793–802, Mar. 2005.

[40] J. S.Warren *et al.*, “Cosmic-Ray Acceleration at the Forward Shock in Tycho’s Supernova Remnant: Evidence from Chandra X-Ray Observations,” ApJ, vol. 634, pp. 376–389, Nov. 2005.

[41] S.Katsuda *et al.*, “X-ray Measured Dynamics of Tycho’s Supernova Remnant,” ApJ, vol. 709, pp. 1387–1395, Feb. 2010.

[42] E. M.Reynoso *et al.*, “The Environs of Tycho’s Supernova Remnant Explored through the H I 21 Centimeter Line,” AJ, vol. 117, pp. 1827–1833, Apr. 1999.

[43] J.Lee *et al.*, “The Environment of Tycho: Possible Interaction with the Molecular Cloud,” ApJ, vol. 605, pp. L113–L116, Apr. 2004.

[44] Z.Cai *et al.*, “Distribution of the Molecular Gas Around SN 1572,” *Chinese Astronomy and Astrophysics*, vol. 33, pp. 393–402, Oct. 2009.

[45] E.Carmona *et al.*, “Observation of selected SNRs with the MAGIC Cherenkov Telescope,” *ArXiv e-prints 0907.1009*, Jul. 2009.

[46] V.Acciari and VERITAS, *in preparation*, 2010.

[47] O.Celik, “Observations of the Crab Nebula and Pulsar with VERITAS,” in *International Cosmic Ray Conference*, ser. International Cosmic Ray Conference, vol. 2, 2008, pp. 847–850.