Mini-Proceedings of the Workshop on High Energy Galactic Physics

May 2010

Columbia University

Editors
E. Aliu, R. Mukherjee and J. Holder

Organized by the Barnard College Physics Department and

Sponsored by Barnard College,
Columbia University
and the US National Science Foundation

Foreword

The Workshop on High Energy Galactic Physics was held on the Barnard College and Columbia University campuses on Friday May 28th and Saturday May 29th, 2010. All the presentations and some of the proceedings of this workshop is available as eConf C1005281

Ester Aliu and Reshmi Mukherjee
Organizing Committee

Acknowledgements

Many people must be thanked for contributing to the success of the Workshop on High Energy Galactic Physics. On the one hand, all speakers who accepted the invitation to come to New York on short notice, since the idea of the workshop was conceived only four months before it took place. Also, thanks to all attendants for participating in the scientific discussions that took place in the two days the workshop lasted. They were responsible for making the workshop a success, and we hope to continue on the several collaborations that were formed at the workshop to study Galactic sources of high energy gamma ray emission.

Ester Aliu
on behalf of the Scientific Organizing Committee

Workshop Organization

E. Aliu	Barnard College, Columbia University
R. Mukherjee	Barnard College, Columbia University
J. Holder	Bartol Research Institute, University of Delaware

CONTENTS

Supernova Remnants and Pulsar Wind Nebulae

Supernova Remnants and Pulsar Wind Nebulae

Session Chair: Rene Ong

Recent VERITAS results on SNRs and PWNe — *Scott Wakely*

Session Chair: Martin Pohl

Gamma-ray emission from SNRs — *Don Ellison*

Maser emitting remnants — *John Hewitt*

Pulsar Wind Nebulae: A Multiwavelength Perspective — *Pat Slane*

Recent VERITAS Results on Galactic Supernova Remnants and Pulsar Wind Nebulae

Scott P. Wakely, for the VERITAS Collaboration
Enrico Fermi Insitute &
Department of Physics &
Kavli Institute for Cosmological Physics
University of Chicago
Chicago, IL USA

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 discovery 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 its 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

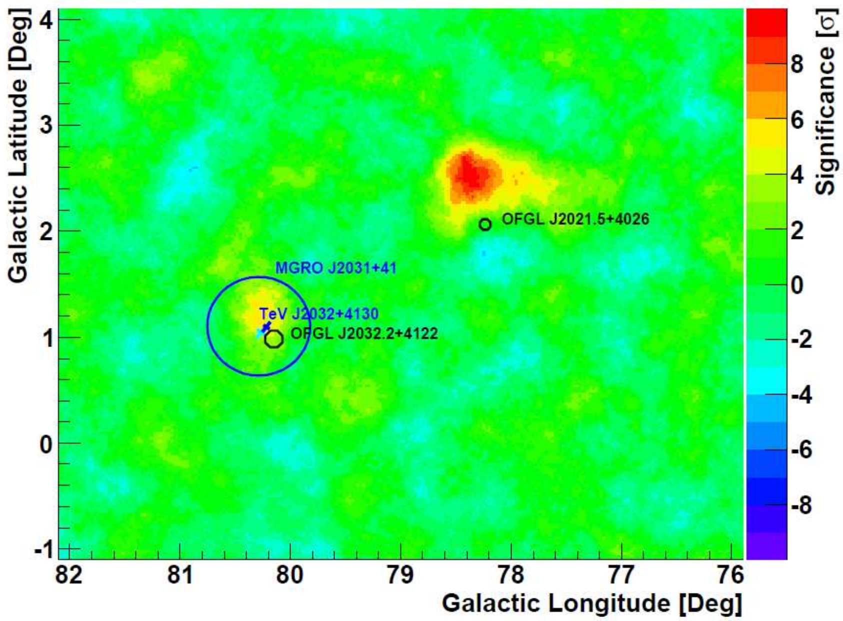

Figure 1: Significance map of a portion of the VERITAS sky survey map, including all follow-up data taken through autumn 2009. The error circles of two Fermi/LAT Bright Sources[4], 0FGL J2021.5+4026 and 0FGL J2032.2+4122, are indicated by black circles. The position of TeV J2032+4130 as measured by HEGRA 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].

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 telescopes or their operation, see [1] or [2]. A recent review of the atmospheric Cherenkov technique can be found in [3].

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 candidate for such a search, due to the presence in the region of a 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 $\ell = 80.3°, b = 1°$, 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 ($\sim 0.2°$) 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 ($\sim 1°$) remnant of a relatively nearby ($\sim$ 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 ($\sim$ 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 ($\sim$ 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 $\sim$ 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-Nebula-level emission (above 300 GeV) is consistent with the location of reported OH maser emission (which is considered to be 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 the Crab Nebula flux above 600 GeV) come from the HEGRA Collaboration[29]. VERITAS observed G54.1+0.3 for ~ 36 hours in 2008/2009, after partial-moonlight observations in 2007 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 [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, the Fermi/LAT Bright Source 0FGL J2229.0+6114 is consistent with the location of the pulsar[4], and the extended super-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 Nebula flux above 220 GeV, centered on the pulsar position[36].

VERITAS observations of G106.3+2.7, motivated by the pulsar energetics, were made in 2007 and 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[37].

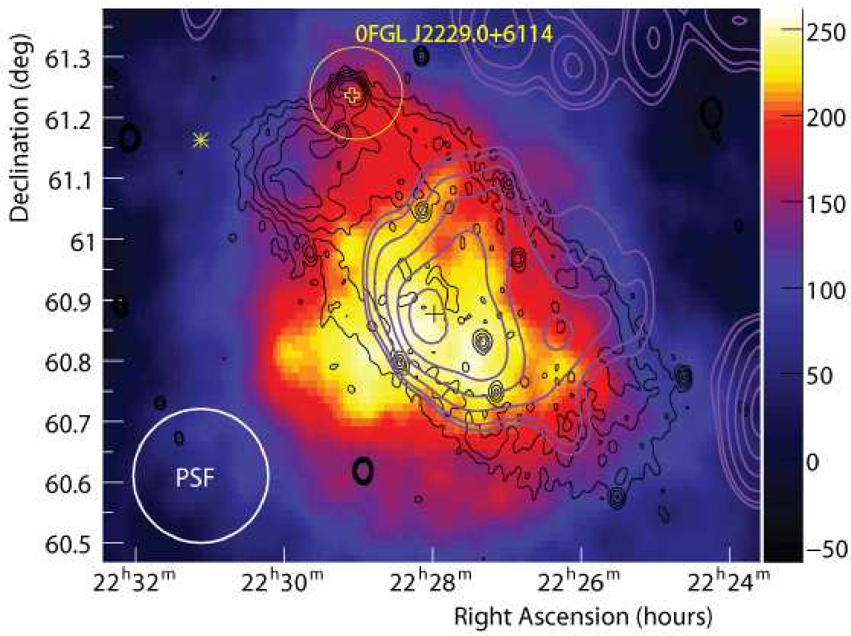

Figure 2: Sky map of TeV gamma-ray emission from G106.3+2.7, as measured by VERITAS. The color scale indicates the number of excess gamma-ray events from the region, using a squared integration radius of 0.08 deg^2. The centroid of the TeV emission is indicated with a thin black cross. Overlaid are 1420 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].

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[38, 39, 40]. 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., [41, 42, 43]). Overall, the mean expansion rate of the remnant suggests a progression

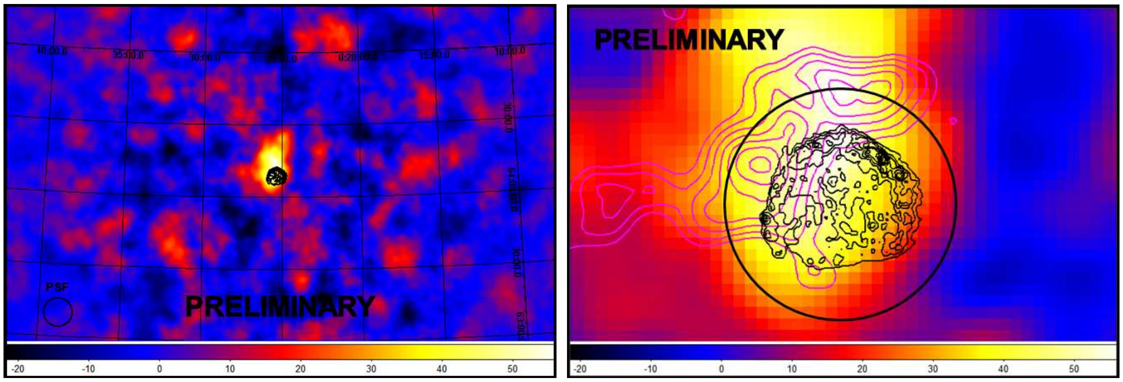

Figure 3: Preliminary VERITAS excess maps of TeV gamma-rays from the direction of Tycho. Left: Wide view of the remnant with superimposed X-ray contours from the Chandra ACIS[39]. Right: Zoomed image of the center of the remnant, again with black contours from the Chandra ACIS. The magenta contours are ^{12}CO data from the FCRAO Survey[33], centered on -64 km/s[42]. 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.

into the Sedov phase and a detailed X-ray study of the shock dynamics[39] 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[44], 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 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[45].

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	[46]
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	[45]

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

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.

Acknowledgements

This research is supported by grants from the U.S. Department of Energy, the U.S. National Science Foundation, NASA, and the Smithsonian Institution, by the Natural Sciences and Engineering Research Council (NSERC) in Canada, by Science Foundation Ireland and by the Science and Technology Facilities Council in the UK. The research presented in this 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] Weekes *et al.*, “VERITAS: the Very Energetic Radiation Imaging Telescope Array System,” *Astroparticle Physics*, vol. 17, pp. 221–243, May 2002.

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

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

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

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

[9] 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] Ladouceur and Pineault, "New perspectives on the supernova remnant G78.2+2.1," A&A, vol. 490, pp. 197–211, Oct. 2008.

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

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

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

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

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

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

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

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

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

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

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

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

[37] de Jager and Djannati-Ataï, “Implications of H.E.S.S. observations of pulsar wind nebulae,” *ArXiv e-prints 0803.0116*, Mar. 2008.

[38] 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.

[39] 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.

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

[41] 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.

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

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

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

[45] Acciari and VERITAS, *in preparation*, 2010.

[46] 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.

Broad band and Gamma-ray emission from SNRs

Don Ellison
Department of Physics
North Carolina State University
NC 27606, USA

Abstract

I report on a model for the broad-band emission from SNR J1713 including a consistent calculation of thermal X-ray emission together with non-thermal emission in a nonlinear diffusive shock acceleration (DSA) model (Ellison et al. 2010, ApJ). This model tracks the evolution of the SNR including the plasma ionization state between the forward shock and the contact discontinuity. We use a plasma emissivity code to predict the thermal X-ray emission spectrum assuming the initially cold electrons are heated either by Coulomb collisions with the shock heated protons (the slowest possible heating), or come into instant equilibration with the protons. For either electron heating model, electrons reach X-ray emitting temperatures rapidly and the X-ray line emission near 1 keV is more than 10 times as luminous as the underlying thermal continuum. Since recent Suzaku observations show no detectable line emission, this places a strong constraint on the unshocked ambient medium density and on the electron to proton ratio. For the uniform circumstellar medium (CSM) models we consider, the low densities and high electron to proton ratios required to match the Suzaku X-ray observations definitively rule out pion-decay as the emission process producing GeV-TeV photons in this particular SNR. We show that a leptonic model, where inverse-Compton scattering against the cosmic background radiation dominates the GeV-TeV emission, can produce a satisfactory fit to the broad-band thermal and non-thermal observations in a uniform CSM.

Maser emitting remnants

John W. Hewitt
GSFC
MD 20771, USA

Abstract

Supernova remnants (SNRs) interacting with molecular clouds are potentially exciting systems in which to detect evidence of cosmic ray acceleration. The nearby cloud serves as a massive target for cosmic rays accelerated by the remnant, producing prominent gamma-ray emission at GeV and TeV energies. A strong correlation is seen between such gamma-ray sources and the presence of OH(1720 MHz) masers. These "SNR masers" allow the interaction with the cloud to be clearly isolated, providing a kinematic distance to the system. The high column of hydroxyl required for masing to occur, is not expected from shock models. An indirect source of ionization in the post-shock gas is needed. If gamma-ray emission from maser-emitting remnants is hadronic in nature, the abundant cosmic rays recently accelerated by the SNR are a significant source of ionization. Fermi LAT has detected gamma-ray emission from half of the known maser-emitting SNRs. The luminosity of GeV emission is consistent with expectations given the mass of the nearby cloud and the expectation that 5% of the total kinetic energy of the supernova remnant is converted to cosmic rays. Those maser-emitting SNRs which are not detected are interacting with too small a cloud at too great a distance to be detected at the current sensitivity, though they can be expected to be detected in the near future. Interestingly, all maser-emitting remnants may have a spectral break between GeV and TeV energies. It has been suggested that a spectral break is due to either the acceleration or diffusion of cosmic rays. The combination of Fermi and VERITAS will permit an important study of this feature, probing the physics of cosmic ray acceleration and propagation for a large sample of remnants.

Pulsar Wind Nebulae: A Multiwavelength Perspective

Pat Slane
Harvard-Smithsonian Center for Astrophysics
Cambridge, MA 02138, USA

Abstract

The extended nebulae formed as pulsar winds expand into their surroundings provide information about the composition of the winds, the injection history from the host pulsar, and the material into which the nebulae are expanding. Observations from across the electromagnetic spectrum provide constraints on the evolution of the nebulae, the density and composition of the surrounding ejecta, the geometry of the central engines, and the long-term fate of the energetic particles produced in these systems. Such observations reveal the presence of jets and wind termination shocks, time-varying compact emission structures, shocked supernova ejecta, and newly formed dust. Here I provide a broad overview of the structure of pulsar wind nebulae, with specific examples from observations extending from the radio band to very high energy gamma-rays that demonstrate our ability to constrain the history and ultimate fate of the energy released in the spin-down of young pulsars.

Binary Systems and other objects

Binary Systems and other objects

Session Chair: Brian Humensky

Puzzling gamma-ray binaries from a Fermi perspective	*Richard Dubois*
TeV observations of Galactic binary systems with VERITAS	*Jamie Holder*
TeV results on Cyg X-3 by MAGIC	*Roberta Zanin*
Black widows and other binaries	*Mallory Roberts*
On TeV emission from magnetars	*Eric Gotthelf*

Puzzling Gamma-Ray Binaries from a Fermi perspective

Richard Dubois
SLAC
CA 94025, USA

Abstract

Results from the first two year of Fermi LAT (Large Area Telescope) observations of the bright sources LS I +61 303 and LS 5039, well observed binary systems at X-ray and TeV energies, have yielded new questions at GeV energies about their nature. In survey mode the LAT observes every point in the sky every 3 hours making it an ideal monitor for these systems. These sources are proving to be surprising in terms of spectral behaviour and variability. The exponential cutoff seen in both sources is very reminiscent of the many pulsars Fermi has found, yet the orbital variability we see, consistent with inverse Compton scattering, is not expected in that interpretation. In addition, LS I +61 303 has shown remarkable, abrupt changes in its flux levels and orbital modulation, as well as a recent absence of TeV emission at apastron as reported by VERITAS and MAGIC. Torres has suggested that we are seeing the effects of both pulsar magnetospheric emission and pulsar wind to accommodate both seemingly exclusive properties. The LAT team is pursuing a follow-up publication for these two sources to exploit the additional data since the initial papers for each.

TeV observations of Galactic binary systems with VERITAS

Jamie Holder for the VERITAS Collaboration
Department of Physics and Astronomy and the Bartol Research Institute
Unversity of Delaware
DE 19716, USA

1 Introduction

High Energy (HE; 30 MeV - 30 GeV) and Very High Energy (VHE; 30 GeV - 30 TeV) gamma-ray emission has been detected from a number of galactic binary systems in recent years. The association of the gamma-ray source with the binary system is definitive in those cases where orbital modulation of the gamma-ray flux is observed. Binary systems which emit gamma-rays constitute a source class with rather indistinct boundaries, with few members, displaying wide variation in the properties of the binary components and the observed emission characteristics. Nevertheless, as natural particle accelerators operating under varying, but regularly repeating, environmental conditions, they provide a uniquely constraining environment for models of particle acceleration and gamma-ray production and emission processes.

The observational status can be summarized as follows. Clear HE and VHE detections exist for the known high-mass X-ray binary systems LS I +61°303 [1, 2, 3] and LS 5039 [4, 5], while Cyg X-3 and PSR B1259-63 have been detected only at HE [6, 7] and VHE [8] respectively. Evidence at the 4.1σ level for VHE emission from the stellar mass black hole candidate Cyg X-1 has been reported by Albert et al. [9] during a single short flaring episode, and transient HE emission has been reported by AGILE [10], but is not confirmed by contemporaneous Fermi-LAT observations, which place limits appreciably below the reported AGILE flux [11]. HE detections of a gamma-ray source co-located with Eta Carina [12, 13] can be interpreted as particle acceleration in the colliding wind region between the two massive stars which make up the system, although the absence of a clear orbital modulation signature lends support to alternative explanations unrelated to the binary nature of the system (e.g. [14]). The recent Fermi-LAT detection of transient HE emission associated with a nova outburst of the symbiotic star system V407 Cyg [15] adds a new and unexpected member to the class of gamma-ray binaries. Finally, the unidentified HESS source HESS J0632+057 has been proposed as a VHE binary candidate [31], although the binary identification in this case remains far from certain.

VERITAS [16] is an array of four, 12 m diameter imaging atmospheric Cherenkov telescopes used for gamma-ray astronomy in the VHE regime. The array has been fully operational since 2007 and, following the relocation of the prototype telescope to a more favorable location in summer 2009, has sufficient sensitivity to detect a source with 1% of the flux of the Crab Nebula in $\sim$ 30 hours. Deep observations of numerous binary systems have been made with VERITAS over the past few years. In these proceedings we report on some recent measurements of LS I +61°303, HESS J0632+057 and 1A 0535+262.

2 LS I +61°303

LS I +61°303 is a high-mass X-ray binary system consisting of a compact object, either black hole or neutron star, orbiting a B0Ve companion with a mass of $\sim$12.5 $M_\odot$ and a circumstellar disk. The orbital period is 26.5 days, and the orbit is eccentric ($e = 0.537$), with the separation between the binary components varying from $\sim$ 0.1 A.U. at periastron, to $\sim$ 0.7 A.U. at apastron.

The detection of extended structures in radio observations identified LS I +61°303 as a potential microquasar, with high energy emission produced in jets driven by accretion onto the compact object, presumably a black hole [17]. More recent observations indicate that the radio structures are not persistent, and can be more easily explained by the interaction between a pulsar wind and the wind of the stellar companion [18, 19], although alternative interpretations are still possible [20, 21].

High energy emission, spatially coincident with LS I +61°303, although with large positional errors, was detected by COS-B [22] and EGRET [23]. The detection of a variable VHE source at the location of LS I +61°303 with MAGIC [1], later confirmed by VERITAS [2], completed the identification of this source as a gamma-ray binary. The VHE emission reported by both experiments for observations made prior to 2008 is spread over approximately one quarter of the orbit, with a peak around apastron (orbital phase $\phi = 0.775$). Fermi-LAT observations provided the definitive HE detection and have revealed a number of interesting features [3]. The HE emission reported in the detection paper is modulated at the orbital period, with an emission peak slightly after periastron ($\phi = 0.225$). The overall spectrum shows a sharp exponential cutoff at 6 GeV, and so does not connect smoothly with the published VHE spectra.

The existence of orbital modulation in the gamma-ray flux is often explained by the varying efficiency of the inverse Compton process around the orbit, although we note that many alternative explanations exist (see e.g. [24] for a review). In this scenario, inverse Compton gamma-ray production along our line of sight is most efficient at superior conjuction ($\phi = 0.081$), where stellar photons interact head-on with energetic leptons produced either directly in the pulsar wind or in the pulsar wind/ stellar wind shock interaction region. The density of stellar photons also plays a role in the efficiency of gamma-ray production, with the highest density occurring at periastron. The VHE flux is further modulated by photon-photon absorption around the orbit, which peaks near superior conjuction and may dominate over the modulation effects due to production efficiency at energies above ~ 30 GeV. Orbital modulation of the HE and VHE flux, with large differences between the lightcurves observed in each energy band, is therefore not unexpected. Other effects, for example Doppler boosting of the emission [25] or cascading of high energy photons to lower energies may also play a role and provide a better fit of the models to the observations.

Two observational features are not yet well explained, and to some extent have been misinterpreted in most of the modelling work thus far. The first is the existence of the 6 GeV cut-off in the Fermi-LAT spectrum. This feature is too low in energy to be explained by pair absorption, and so might possibly point towards a different origin for the HE and VHE emission; for example, the HE emission might be largely magnetospheric, since similar cut-offs are observed in many Fermi-LAT pulsar spectra [3]. In this case, however, it is difficult to explain the observed orbital modulation of the HE flux. A key point to note is that the published HE/VHE spectra are comprised only of non-contemporaneous observations. All of the VHE observations were made before the launch of Fermi, and contain only data taken during apastron high states. **There is no direct evidence that the VHE emission continues beyond the Fermi-LAT cutoff, for observations made at the same time**.

Figure 1 summarizes VERITAS observations since the launch of Fermi. In 2008-9, apastron coverage was limited due to bright moon conditions. VERITAS observations therefore focussed on attempting to obtain reasonably deep coverage over a wide phase range, during two orbital cycles. Only marginal evidence (3.4 σ) for a gamma-ray signal in the complete 37 hour dataset was obtained [26], and upper limits in each phase bin are presented in the figure. In 2009-2010, apastron was visible during full dark time, and so observations were targeted towards deep exposures at this phase. 18 hours of data were collected over three orbital cycles, resulting in no significant gamma-ray excess (0.8 σ). The upper limits, particularly around apastron phases in 2009-2010, are significantly below the previously reported fluxes; in the case of VERITAS this is due, in part, to the fact that the observations were made with a much more sensitive instrument, since the early detections were made during the array construction phase. These results lead to the second observational feature we wish to highlight; **there is no strong evidence for VHE gamma-ray emission from LS I +61°303 since the launch of Fermi-LAT**. A corollary to this observation is that there is no direct evidence that the HE and VHE lightcurves are in anti-phase with each other, as is often assumed. It should also be stressed that the recent VERITAS observations do not prove that VHE emission has been completely absent since the launch of Fermi; as shown in Figure 1, the sampling is extremely limited, and even during those periods where observations were made, each observation consisted

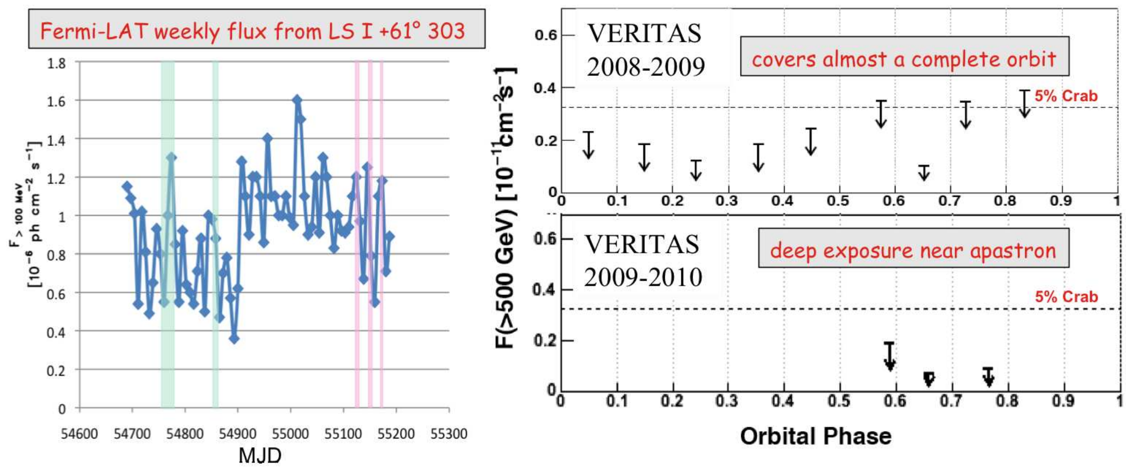

Figure 1: VERITAS observations of LS I +61°303 since the launch of Fermi-LAT. On the left is shown the LAT weekly lightcurve (courtesy of R. Dubois), with the VERITAS observation periods indicated by shaded bands. Observations during each shaded band consisted of a series of up to two hour exposures, separated by at least one day. Orbital phase-binned upper limits for the two observing seasons are shown on the right.

of typically 1-2 hour exposures, separated by at least a day. Variability from the source has been observed at X-ray wavelengths on timescales from hours to as short as a few seconds [28]. The VHE emission may be similarly variable, or there may be significant orbit-to-orbit variability; either case could simply explain the VERITAS observations.

A further interesting observational feature was presented at this conference [27]. In March 2009 the average HE flux observed by Fermi-LAT increased by $\sim$ 40%. Additionally, a periodic analysis of LAT data since the flux increase shows no strong evidence for orbital modulation of the flux. Clearly, the gamma-ray emission of LS I +61°303 cannot be simply characterized. The solution to this lies in future broadband, contemporaneous, coordinated observing campaigns, as are frequently arranged for the gamma-ray blazars.

3 HESS J0632+057

HESS J0632+057 is an unidentified VHE source, serendipitously detected using the H.E.S.S. imaging atmospheric Cherenkov array during observations of the region of the Monoceres supernova remnant and the Rosette Nebula [29]. The source is unusual among unidentified VHE sources in that it is unresolved, with an upper limit to the extension of 2'. Observations at other wavelengths have revealed a faint, variable

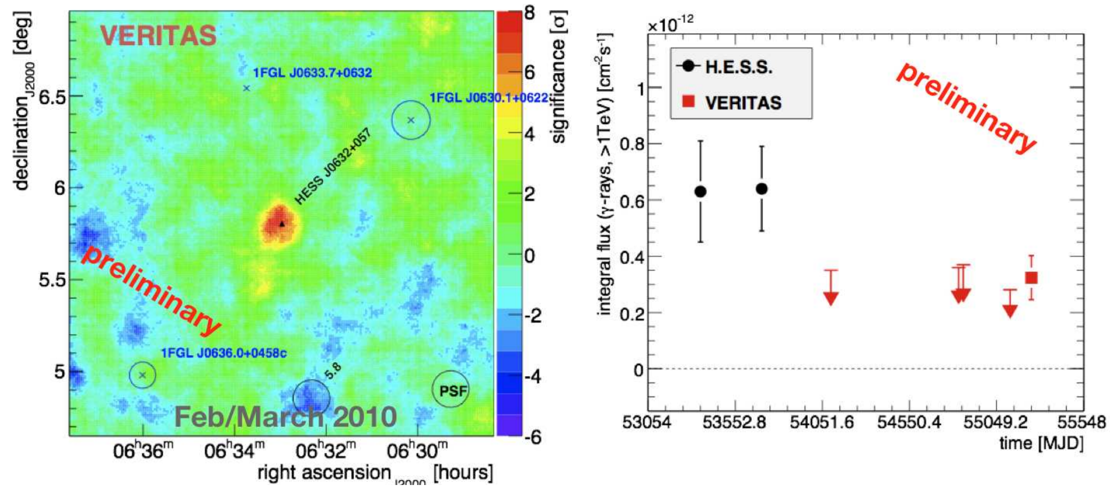

Figure 2: VERITAS observations of HESS J0632+057. On the left is shown the VERITAS significance map for a 20 hour exposure in February/March 2010. The right-hand plot shows the complete H.E.S.S./VERITAS VHE lightcurve.

radio source [30], and a variable, hard spectrum X-ray source [31, 32], with positions compatible with that of HESS J0632+057, and also with the location of MWC 148, a B0pe star. These features have led to the suggestion that HESS J0632+057 may be a gamma-ray binary system, previously unidentified at other wavelengths [31].

Further weight was added to this argument by VERITAS observations of the source made in 2006, 2008 and 2009 totalling 30 hours, which failed to detect any evidence for gamma-ray emission, thus establishing the source as variable in the VHE band (at the 4σ confidence level) [33]. Figure 2 shows the result of new observations with VERITAS from the 2009/2010 observing season, which verify this result. An 8 hour exposure in October 2009 did not detect the source, while a 20 hour exposure in February/March 2010 led to a clear detection (7.5 σ), with a position in agreement with both HESS J0632+057 and MWC 148, and a flux of $\sim$ 50% of the original H.E.S.S. detection. Extended multiwavelength campaigns are again necessary to establish the nature of this object. The detection of an orbital periodicity in the emission at any wavelength would provide definitive evidence for the presence of a binary system.

4 1A 0535+262

1A 0535+262 is a high mass X-ray binary system at a distance of 2.4 ± 0.4 kpc, consisting of a Be star (spectral type O9.7IIIe) and a magnetized X-ray pulsar with a spin period of 104 s [34]. The binary period is 110 days, and the orbital eccen-

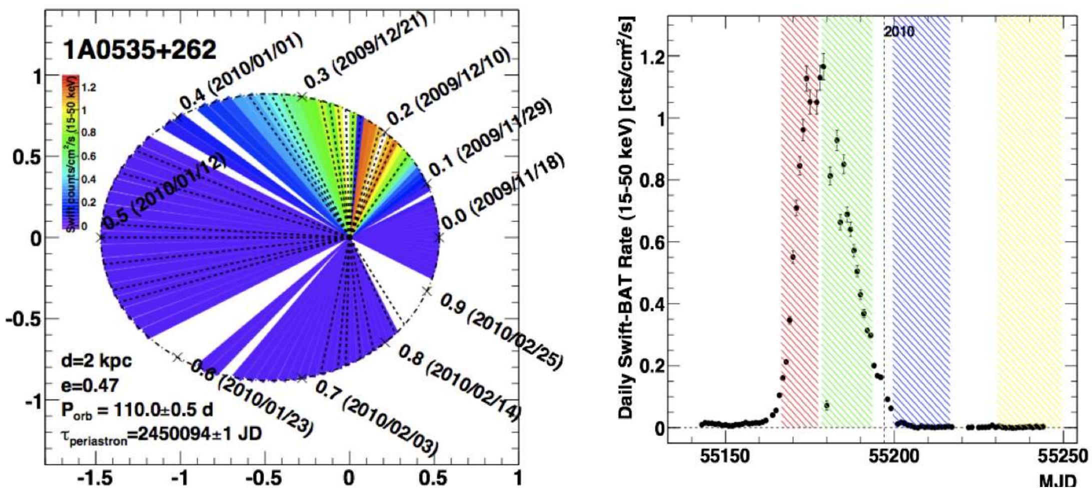

Figure 3: VERITAS observations of 1A 0535+262. On the left is shown the orbit of the binary system. The colour scale of the shaded regions indicates the Swift-BAT $15-50$ keV count rate; the dashed lines indicate the dates of VERITAS observations. The right-hand plot shows the Swift-BAT count rate ligt curve. The four shaded regions indicate the division of VERITAS data into rising (red) and falling (green) flare edges, apastron (blue), and approaching periastron (yellow).

tricity, $e = 0.47$ [35]. The source shows luminous "Type II" X-ray outbursts, with much higher peak fluxes than the "Type I" bursts associated with periastron passage. Type II bursts have occurred approximately every 5 years since the first X-ray detection in 1975 and typically last for ~ 1 month. The hard X-ray spectrum observed during these outbursts points to the existence of non-thermal particle populations. Orellana & Romero [36] have discussed the possibility of VHE emission from systems such as this through a scenario in which relativistic protons, accelerated through the Cheng-Ruderman mechanism [37], impact the surface of a transient accretion disk and produce gamma-rays via neutral pion decay.

In December 2009 the detection of a giant X-ray outburst from 1A 0535+262 [38, 39] triggered observations with VERITAS. The source was regularly monitored from December 6th 2009 (MJD 55171) until February 20th 2010 (MJD 55247), yielding a total exposure of 28 hours covering almost one complete 110 day orbital cycle. The X-ray flare itself lasted for ~ 40 days and reached a peak flux of ~ 5 Crab in the Swift-BAT $15-50$ keV range, making this the brightest outburst ever observed from this source. Figure 3 details the VERITAS coverage with respect to the binary orbit and the X-ray flare. No evidence for gamma-ray emission was detected, either in the complete dataset or when the data were divided into four subsets covering the rising and falling edges of the flare, and two post-flare periods at apastron and approaching periastron. The outburst occurred at an ideal time for VERITAS observations, with the instrument operating at its highest sensitivity to-date, during a period of dark, clear skies and without strong competition from other source candidates. Since such outbursts occur only once every five years, and since 1A 0535+262 is the most well studied of the Be/X-ray binaries showing Type II outbursts, these data likely provide the definitive results on this source class for this generation of imaging atmospheric Cherenkov telescopes.

5 Acknowledgments

This research is supported by grants from the US Department of Energy, the US National Science Foundation, and the Smithsonian Institution, by NSERC in Canada, by Science Foundation Ireland, and by STFC in the UK. We acknowledge the excellent work of the technical support staff at the FLWO and the collaborating institutions in the construction and operation of the instrument.

This work has used data from the Swift/BAT Hard X-ray Transient Monitor web page.

J. Holder acknowledges the support of the NASA Fermi Cycle 2 Guest Investigator Program (grant number NNX09AR91G).

References

[1] J. Albert, et al., Science, 312, 1771, 2006.

[2] V.A. Acciari, et al., ApJ, 679, 1427, 2008.

[3] A.A. Abdo, et al., ApJ, 701, L23, 2009.

[4] F.A. Aharonian, et al., A&A, 460, 743, 2006.

[5] A.A. Abdo, et al., ApJ, 706, L56, 2009.

[6] M. Tavani, et al., Nature, 462, 620, 2009.

[7] The Fermi LAT Collaboration, Science, 326, 1512, 2009.

[8] F.A. Aharonian, et al., A&A, 442, 1, 2005.

[9] J. Albert, et al., ApJ, 665, L51, 2007.

[10] S. Sabatini, et al., ApJ, 712, L10, 2010.

[11] R. Dubois, et al., "Proc. ICREA Workshop on The High-Energy Emission from Pulsars and their Systems", Sant Cugat, Spain, April 12-16, 2010

[12] M. Tavani, et al., ApJ, 698, L142, 2009

[13] A.A. Abdo, et al., ApJSupp., 188, 405A, 2010

[14] S. Ohm, J.A. Hinton & W. Domainko, ApJL *preprint arXiv:1006.2464*

[15] C.C. Cheung, et al., Astronomer's Telegram #2487, 2010.

[16] R.A. Ong, et al., in "Proc 31st ICRC", Lodz, Poland, 2009, *preprint arXiv:0912.5355*

[17] M. Massi, et al.,A&A, 376, 217, 2001.

[18] V. Dhawan, et al., in "Proc. of the VIth Microquasar Workshop: Microquasars and Beyond", Como, 2006.

[19] J. Albert, et al., ApJ, 684, 1351, 2008.

[20] G.E. Romero, et al., A&A, 474, 15, 2007.

[21] M. Massi & L. Zimmerman, A&A, 515, 82, 2010.

[22] W. Hermsen, et al., Nature, 269, 494, 1977.

[23] M. Tavani, et al., ApJ, 497, L89, 1998.

[24] A. Sierpowska-Bartosik, & D. Torres, ApJ, 693, 1462, 2009

[25] G. Dubus, B. Cerutti & G. Henri, A&A, 516, 18, 2010.

[26] J. Holder, et al., in "Proc 31st ICRC", Lodz, 2009.

[27] R. Dubois et al., these proceedings.

[28] A. Smith, et al., ApJ, 693, 1621, 2009.

[29] F.A. Aharonian, et al., A&A, 469, L1, 2007.

[30] J.L. Skilton, et al., MNRAS, 399, 317, 2009.

[31] J.A. Hinton, et al., ApJ, 690, L101, 2009.

[32] A.D. Falcone, et al., ApJ, 708, L52, 2010.

[33] V.A. Acciari, et al., ApJ, 698, L94, 2009.

[34] A. Giangrande, et al., A&AS, 40, 289, 1980.

[35] M. Finger, R.B. Wilson & B.A. Harmon, ApJ, 459, 288, 1996.

[36] M. Orellana & G.E. Romero, Ap&SS, 297, 167, 2005.

[37] K.S. Cheng & M. Ruderman, ApJ, 373, 187, 1991

[38] C.A. Wilson-Hodge, et al., Astronomer's Telegram #2324, 2009.

[39] H.A. Krimm, et al., Astronomer's Telegram #2336, 2009.

MAGIC observations of Cygnus X-3

Roberta Zanin, on behalf of the MAGIC collaboration
Institut de Fisica d'Altes Energies
Ed. Cn., Campus U.A.B.
E-08193 Bellaterra, Barcelona SPAIN

1 Introduction

Cygnus X-3 is a bright X-ray binary which has been classified as microquasar due to the detection of collimated relativistic jets at radio frequencies [1]. It consists of an accreting compact object, whose nature is still unknown, black hole or neutron star, and a Wolf-Rayet companion star [3]. This high-mass X-ray binary system, lying at a distance of $\sim$7 kpc [4] close to the Galactic plane, shows a short orbital period of 4.8 hours [2].

The source shows two main X-ray spectral states, the soft and the hard one, which are similar to the canonical states of the black hole binaries [5, 6]. The hard state (HS) is dominated by a non-thermal power-law emission peaking at 20 keV [7]; whereas the soft state (SS) is characterized by a strong thermal component with a non-thermal tail. A finer classification of the spectral states was obtained by analyzing the correlation between X-ray and radio fluxes. The six identified X-ray/radio states are: quiescent, minor-flaring, suppressed, quenched, major-flaring, and post-flaring [8, 9, 10].

Microquasars have always been considered good targets for very-high-energy (VHE) astrophysics. They are believed to produced such VHE radiation inside the jets: its origin can be connected either to the presence of steady and compact jets which appear when the source is in a HS [11], or to strong radio ejections [12] mainly occurring during the SS.
In the 80's, many claims of detection at TeV and PeV were published raising the interest on this source, even though these results could not be confirmed by more sensitive instruments [13, 14].

In the high-energy (HE) range, the Energetic Gamma-Ray Experiment Telescope (EGRET) detector observed an average flux of 8.2×10^{-7} photons cm^{-2} s^{-1} at energies above 100 MeV coming from the direction of Cygnus X-3 [15]. However, no strong association with the microquasar was possible, since no orbital modulation was detected. Lately both *Fermi*/LAT and *AGILE* collaborations reported the detection of Cygnus X-3 at energies larger than 100 MeV [16, 17]. *Fermi*/LAT detected the source at more than 29σ during two periods of enhanced activity in the HE band, corresponding to the source being in the SS. Abdo et al.(2009) showed also an orbital modulation of the flux and a detailed light-curve with peak fluxes as high as 2.0×10^{-6} photons cm^{-2} s^{-1} above 100 MeV. On the other hand *AGILE* detected the microquasar only during its strongest γ-ray ejections which are comparable and simultaneous to the *Fermi*/LAT peak emissions.

The recent successful results obtained by imaging atmospheric Cherenkov telescopes (IACTs) in discovering binary systems [18, 19, 20], together with the favorable theoretical predictions, encouraged deeper observations of microquasars. However, in the particular case of Cygnus X-3, photon-photon absorption cannot be neglected if the γ rays are produced close to the massive companion star [21].

This paper shows the results of the observations of Cygnus X-3 performed with the first stand-alone Major Atmospheric Gamma Imaging Cherenkov (MAGIC, phase I) telescope between 2006 and 2009. In order to look for VHE emission above 250 GeV in the source states in which such a radiation is predicted, the MAGIC observations were planned to cover several X-ray/radio states, including those that showed a strong HE γ-ray flux. Section 2 describes the MAGIC (phase I) telescope and the way the observations of Cygnus X-3 were organized. The obtained results, placed in a multi-wavelength context, are shown in the following section. A short discussion follows in section 4.
Further details on these MAGIC observations of Cygnus X-3 can be found in [22].

2 Observations

MAGIC (phase I) is an IACT located at the Canary island of La Palma (Spain) at 2200 m above sea level. It has a 17 m diameter reflecting dish which collects and focuses the Cherenkov light to a multi-pixel camera equipped with 576 photomultiplier tubes. The performance of the telescope improved over the years thanks to several hardware and software upgrades which made the integral flux sensitivity improve from $\sim 2.5\%$ to $\sim 1.6\%$ of the Crab Nebula flux in 50 hours of observation.

MAGIC collected 56.7 hours of good quality data between March 2006 and August 2009 distributed over 39 nights of observation. The VHE observations were triggered by the source flux at other wavelengths. In 2006, MAGIC received two alerts of a flaring state at radio frequencies from the Russian RATAN-600 telescope (Trushkin, private communication), on March 10 and July 26, 2006 respectively. In 2007, a monitoring campaign of the hard state of Cygnus X-3 was set up. The X-ray spectral state of the source was defined by using public *RXTE*/ASM (1.5–12 keV) and *Swift*/BAT (15–50 keV) data, as follows: a) *Swift*/BAT daily count rate larger than 0.05 counts cm^{-2} s^{-1} and b) ratio between *RXTE*/ASM and *Swift*/BAT count rates lower than 200. During 2008 and 2009, MAGIC observed Cygnus X-3 following two HE γ-ray alerts issued by the *AGILE* team on April 18, 2008 and July 18, 2009 respectively (Tavani, private communication).

The data analysis was carried out using the MAGIC standard calibration and analysis software [23, 24, 25].

3 Results

The search for a time-integrated VHE emission from Cygnus X-3 was performed combining all the available data, and it yielded no significant excess events. The computed 95% confidence level (CL) upper limit (UL) to the integral flux is of 2.2×10^{-12} photons cm^{-2} s^{-1} for energies above 250 GeV. It corresponds to 1.3% of the Crab Nebula flux at these energies. The 95% CL differential flux upper limits, calculated by assuming a power-law spectrum with a photon index of 2.6 are shown in figure 1.

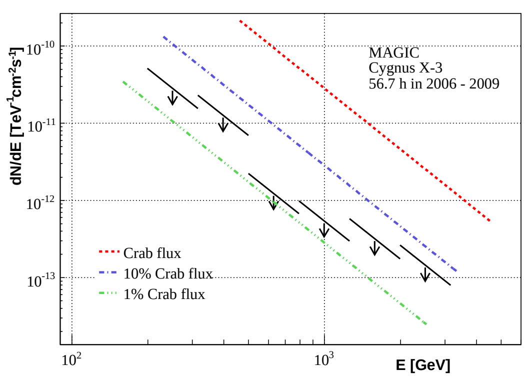

Figure 1: Differential flux upper limits at 95% CL for the VHE time-integrated emission.

Since the source is variable on time scales of days at other wavelengths, data from each day were analyzed separately. No signal was detected during any night of observation. These daily integral flux ULs for energies above 250 GeV are shown in Figure 2, together with HE γ-ray (*AGILE* and *Fermi*/LAT [0.1–30 GeV]), hard X-ray (*Swift*/BAT [15–50 keV]), soft X-ray (*RXTE*/ASM [1.5-12 keV]), and radio measured fluxes from January 1, 2006 until December 15, 2009. The radio measurements were provided by the RATAN-600 telescope at 2.15, 4.8 and 11.2 GHz, and by the Ryle telescope (RT), the Arcminute Microkelvin Imager (AMI) and the Owens Valley Radio Observatory (OVRO) 40-meter telescope at 15 GHz. This figure puts the MAGIC results in a multi-wavelength context allowing us to derive the X-ray/radio spectral state of the source during MAGIC observations.

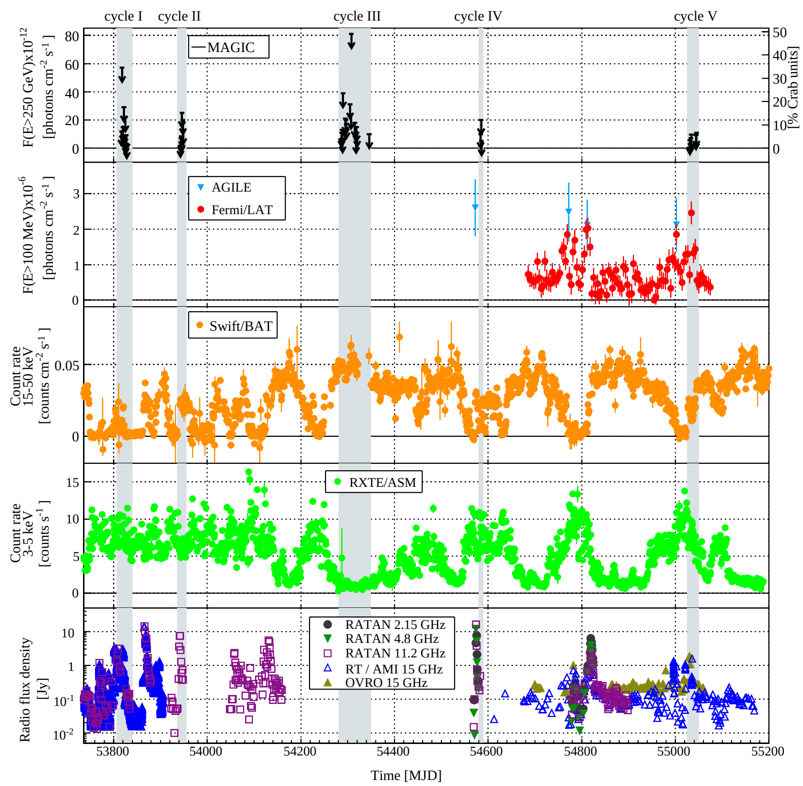

Figure 2: From top to bottom: daily MAGIC VHE integral flux upper limits for E > 250 GeV, and high-energy γ-ray (*AGILE* and *Fermi*/LAT), hard X-ray (*Swift*/BAT), soft X-ray (*RXTE*/ASM) and radio fluxes measured for Cygnus X-3 as function of time (from January 1, 2006 untill December 15, 2009). The gray bands show the periods corresponding to the MAGIC observations.

MAGIC pointed at Cygnus X-3 always in its SS, expect for the 2007 campaign, when the HS was required by the observational trigger. The two 2006 observational campaigns, triggered by radio flares, started when the high-activity at radio frequencies had already ended, but still the source was in a SS. Also in April 2008, following an *AGILE* alert, MAGIC started its observations of Cygnus X-3 ten days after a huge radio flare and an enhanced activity in the HE γ-ray band, but the source was still in the SS. The second *AGILE* alert in July 2009 was much more successful: MAGIC succeeded in taking some data simultaneous with a HE peak emission, detected by both *AGILE* (Bulgarelli et al., in preparation) and *Fermi*/LAT, during which the radio emission was characterized by small flares. The results of this specific subsample are treated in section 3.1.

The MAGIC results were also summarized according to the X-ray spectral state of the source. In fact, VHE emission is thought to be produced either in steady and persistent jets present when the source is in the HS, or during strong radio ejections which mainly occur during the SS. The 95% CL upper limit to the integral flux is of the order of 2.5% and 1.1% of the Crab Nebula flux for the SS and the HS respectively.

Since the predicted VHE emission is expected to be modulated according to the orbital phase due to the highly anisotropic radiation from the companion star [26], phase-folded analyses of both the SS and HS data samples were performed. No periodic signal was found.

3.1 Results during high-energy γ-ray emission

In 2009, MAGIC observed Cygnus X-3 during a period of HE enhanced activity detected by *Fermi*/LAT. In particular, there are two nights on July 21 and 22, 2009, corresponding to ~4 hours of data, which are strictly simultaneous to a *Fermi*/LAT peak emission and an *AGILE* detection (Bulgarelli et al., in preparation), as it can be seen in Figure 3 (the point of the AGILE detection is missing, since it is not public yet). No VHE signal was found in this data subsample, yielding an integral flux UL at the level of 6% of the Crab Nebula flux.

Figure 4 shows the spectral energy distribution (SED) of Cygnus X-3 above 100 MeV for both the SS and the HE peak emission. The SED was computed by using the differential flux MAGIC ULs, and the power-law spectra measured by both *Fermi*/LAT and *AGILE* with a photon index of 2.7 and 1.8, respectively (see [22] for further details).

4 Conclusions

MAGIC did not detect Cygnus X-3 at energies larger than 250 GeV, and set strong UL to the integral flux at the level of 1.3% of the Crab Nebula flux. Also the search for variable and periodic signals yielded no positive detections.
MAGIC observations of Cygnus X-3 cover all X-ray spectral states of the source where VHE emission has been predicted. No VHE signal, above 250 GeV, was found in any of the inspected samples. In particular for the HS, which is foreseen to show a stationary VHE signal coming from persistent jets, the MAGIC UL to the VHE luminosity is 70 times larger than the expected value (10^{32} erg s^{-1}). Therefore, Cygnus X-3 in this spectral state does not seem to be an interesting observational target for the current sensitivity instrumentation.
MAGIC did not detect any VHE emission coming from the microquasar even during

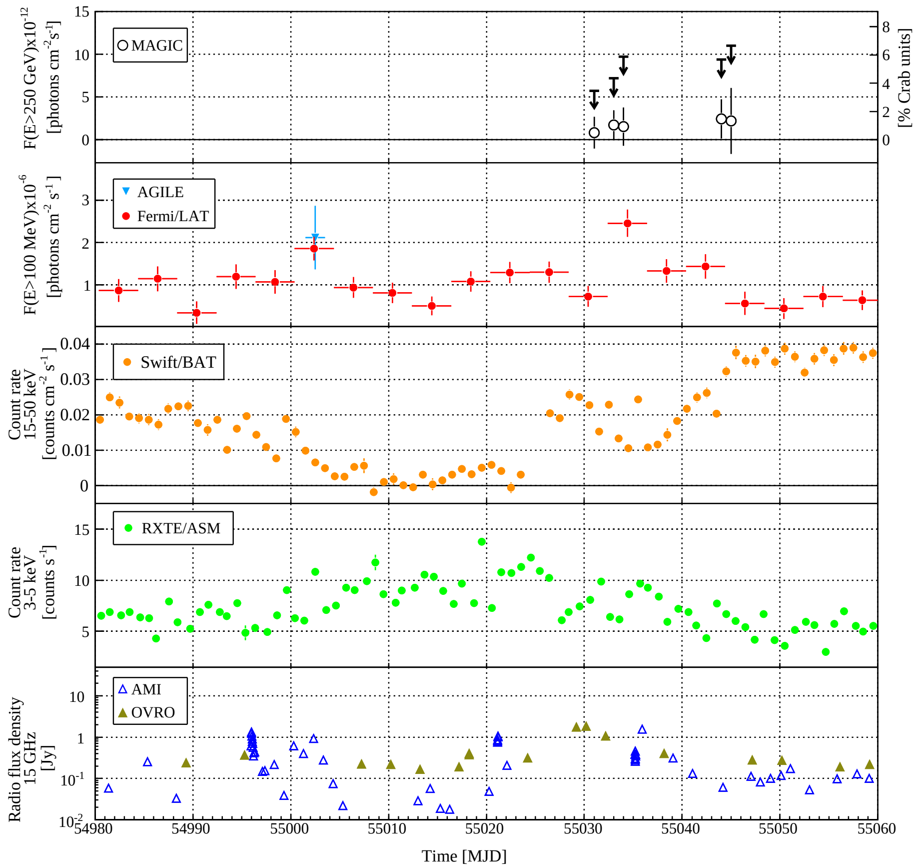

Figure 3: Zoom of Figure 2 between May 29, and August 17, 2009.

a HE γ-ray peak emission. However, MAGIC upper limits are still compatible with the extrapolation of the *Fermi*/LAT power-law (photon index 2.7), but not with the *AGILE* one (photon index 1.8). The latter could suggest a spectrum cut-off between some tens and 250 GeV.
Unfortunately, MAGIC has never observed the source during the raising edge of a radio flare when, according to the synchrotron self Compton scenario, a detectable flare might arise. This might be a remaining task for the new upgraded generation of IACTs, together with the search for signals at much lower energies (lower than 200 GeV).

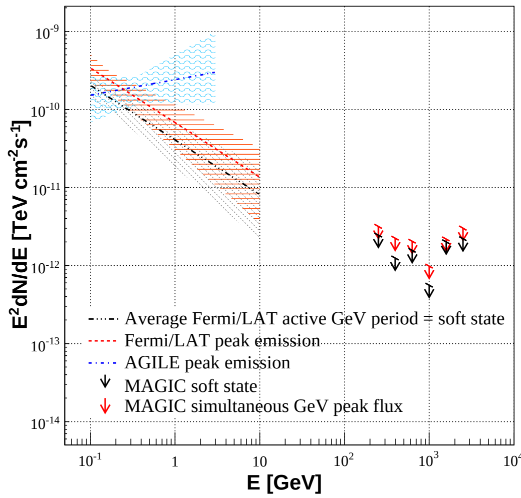

Figure 4: Cygnus X-3 spectral energy distribution in the HE and VHE bands. The lines indicate the power-law spectra derived from *Fermi*/LAT and *AGILE* integral fluxes and photon indices, where the corresponding errors were taken into account and are shown in shadowed areas. The arrows display the 95% CL MAGIC differential flux upper limits and their slope indicates the assumed power-law spectrum with a photon index 2.6. The black indicators show the SED during the period of enhanced GeV activity coinciding with the SS, whereas the red and blue ones during the HS peak emission.

5 Acknowledgment

We would like to thank the Instituto de Astrofisica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The support of the German BMBF and MPG, the Italian INFN, the Swiss National Fund SNF, and the Spanish MICINN is gratefully acknowledged. This work was also supported by the Polish MNiSzW Grant N N203 390834, by the YIP of the Helmholtz Gemeinschaft, and by grant DO02-353 of the the Bulgarian National Science Fund.

References

[1] Martí, J., Paredes, J. M., & Peracaula, M. 2001, A&A, 375, 476

[2] Parsignault, D. R., Gursky, H., Kellogg, E. M., et al. 1972, Nature, 239, 123

[3] van Kerkwijk, M. H., Charles, P. A., Geballe, T. R., et al. 1992, Nature, 355, 703

[4] Ling, Z., Zhang, S. N., & Tang, S. 2009, ApJ, 695, 1111

[5] Zdziarski A. A., & Gierlinski M. 2004, Progr. Theor. Phys. Suppl., 155, 99

[6] Hjalmarsdotter L., et al. 2008, MNRAS, 384, 278

[7] Hjalmarsdotter L., et al. 2004, ESASP, 552, 223

[8] Szostek, A., Zdziarski, A. A., & McCollough, M. 2008, MNRAS, 388, 1001

[9] Tudose, V., et al. 2010, MNRAS, 401, 890

[10] Koljonen K. I. I., et al. 2010, submitted to MNRAS (arXiv:1003.4351)

[11] Bosch-Ramon, V., Romero, G. E., & Paredes, M. J. 2006, A&A, 447, 263

[12] Atoyan A. M., & Aharonian F. A. 1999, MNRAS, 302, 253

[13] Shilling, M., et al. 2001, in Proc. 27th International Cosmic Ray Conference, Hamburg, 2521

[14] Albert, J., et al. 2008a, ApJ, 675, L25

[15] Mori, M., Bertsch, D. L., Dingus, B. L., et al. 1997, ApJ, 476, 842

[16] Abdo, A. A., et al. 2009, Science, 326, 1512

[17] Tavani, M., et al. 2009, Nature, 462, 620

[18] Aharonian, F. A., et al. 2005a, A&A, 442, 1

[19] Aharonian, F. A., et al. 2005b, Science, 309, 746

[20] Albert, J., et al. 2006, Science, 312, 1771

[21] Bednarek W. 2010, submitted to MNRAS (arXiv:1002.1563)

[22] Aleksić, J., et al. 2010, submitted to ApJ (arXiv:1005.0740)

[23] Albert, J., et al. 2008d, NIM, 594, 407

[24] Albert, J., et al. 2008e, NIM, A588, 424

[25] Aliu, E., et al. 2009, Astropart. Phys., 30, 293

[26] Bednarek W. 1997, A&A, 322, 523

TeV Emission from Millisecond Pulsars in Compact Binaries?

Roberts, Mallory S.E.
Eureka Scientific
Oakland, CA, USA

1 The Black Widow Millisecond Pulsar

Millisecond pulsars (MSPs) whose spin periods are shorter than ~ 5 ms are thought to be old neutron stars that have been "recycled" through an extended period of accretion by a low mass companion (see [16] for an overview of these systems). Although there are exceptions, they are usually found in highly circular orbits around low mass ($M_c \lesssim 0.4 M_\odot$) white dwarves. Despite apparently having relatively low magnetic fields ($B \sim 10^8 - 10^9$ G, as inferred from their spin-down assuming magnetic dipole radiation), the spin down power and potential drop across the magnetosphere of the faster MSPs can be similar to that of young pulsars. They have spin-down timescales of billions of years and their typical space velocities are tens to hundreds of km/s, and so MSPs in the Galactic field have generally migrated to relatively high Galactic latitudes. Many MSPs are found in globular clusters (see P. Freire's web page of MSPs in clusters at `http://www.naic.edu/~pfreire/GCpsr.html`) which, due to the concentration of low mass stars, allow the capture of companions suitable for the recycling process. However, it is difficult to determine the intrinsic spin down of MSPs in globular clusters because of their acceleration by the globular cluster's gravitational potential.

There is a class of MSPs which exhibit radio eclipses and tend to have short orbital periods ($P_{orb} \lesssim 24$ hr). Many of these have very low mass companions ($M_c < 0.05 M_\odot$), much lower than expected for being simply a white dwarf left over at the end of a low mass star's evolution. The prototype of these systems is PSR B1957+20, a 1.6 ms pulsar in a 9.2 hr orbit around a $\sim 0.02 M_\odot$ companion [11]. PSR B1957+20 regularly eclipses over $\sim 10\%$ of the orbit, with the radio pulse being delayed by scattering at eclipse ingress and egress, showing that there is significant amounts of intrabinary material [12]. The optical lightcurve of the system shows large orbital variation, consistent with emission from one side of the companion surface being heated by the pulsar. In $H\alpha$ images can be seen a bow shock, which is direct evidence for a strong pulsar wind [15]. *Chandra* X-ray imaging shows a point source and a nebular tail extending downstream from the pulsar motion [20]. The point-source X-rays are orbitally modulated and have a power-law spectrum [13].

The interpretation of these data is that either particle or γ radiation from the pulsar is ablating material from the companion, which material forms an intrabinary shock with the pulsar wind. The compactness of the orbit and the relatively high spin down energy of the pulsar ($\dot{E} \sim 10^{35}$erg/s) gives rise to this phenomenum. Because the pulsar is "eating away" at the remnant of the star from which it accreted material to become an MSP, PSR B1957+20 is referred to as the Black Widow pulsar.

2 Intrabinary Pulsar Wind Shocks

The material ablated from the companion intercepts some fraction of the ultra-relativistic pulsar wind producing a shock region near the surface of the companion and stretching some distance to either side, causing the radio eclipses. The orientation of this shock front changes in respect to Earth as a function of orbital phase. Arons & Tavani presented a model [6] of shock acceleration for the Black Widow, predicting electron acceleration up to 3 TeV. This would then emit unpulsed radio and X-rays through synchrotron emission at the shock front, and higher energies through inverse Compton scattering. If there were systems with more material and/or more compact, the radio pulses could potentially be obscured throughout the orbit and the system visible only as an unpulsed source of X-ray and TeV emission [21]. Despite the orbit having been circularized by the accretion process, orbital modulation of the high energy emission could arise from obscuration by the shock, the magnetic field orientation of the shock, and doppler boosting. The shock distance of only a few light seconds from the pulsar may imply that the B field in the shock and the ratio of magnetic to particle energy in the wind (the magnetization parameter σ) are relatively large compared to what they would be at the much greater distance of a wind being terminated in a shock with the interstellar medium. Raubenheimer et al. [18] looked at the potential TeV emission from PSR B1957+20 and similar systems in more detail and calculated how the luminosity depended on the shock distance, fraction of wind involved, pulsar magnetic field, optical emission of the companion, magnetization of the wind, and the ion fraction of the wind. They determined, however, that the most important factor for the TeV flux is still simply $\dot{E}/d^2$.

The models for X-ray and TeV emission from the Black Widow were adapted [22] for the highly eccentric ($e \sim 0.87$) pulsar/Be star binary system PSR B1259-63/SS2883 when it was first dicovered to have excess non-thermal X-ray emission [8]. When the young pulsar in this system approaches periastron, it passes through the dense equatarial wind of the Be star, exhibiting significant unpulsed radio and TeV emission in addition to increased X-ray luminosity. While the intrinsic pulsar magnetic field and the Be star companion's wind and optical luminosity are all much higher than in the Black Widow, the binary separation is also much larger, on the order of 100 times more distant even at periastron.

3 The Black Widow Class and Their Cousins

Between 1988 and 2007, only 2 other eclipsing MSPs with very low mass companions were discovered in the Galactic field (as listed in the ATNF Pulsar catalog [17]), both with much lower $\dot{E}/d^2$ than B1957+20, This is assuming their dispersion measure derived distances using the NE2001 Galactic free electron density model [9]. An important question is how reliable are NE2001 distance estimates? Accurate parallax measurements since 2001 show that the 20% error estimate is fairly reliable in the Galactic plane, but at mid to high Galactic latitudes where most MSPs are, the NE2001 model systematically underestimates the distance, often by as much as a factor of 2 [7]. This discrepancy is thought to largely be due to the model's assumed value for the Galactic scale height of gas.

Many more "black widows" have been found in globular clusters. In addition, a related class of eclipsing MSPs with short orbital periods have been discovered, the first one in the globular cluster NGC 6397 by the Parkes telescope in Australia [10]. These have companion masses of a few tenths of a solar mass rather than a few hundredths like Black Widows. In several cases where an optical counterpart has been identified, they often appear to have non-degenerate companions where the stellar size is similar to the Roche lobe. This suggests they may still be in the late stages of recycling. These systems I will refer to as "redbacks", an Australian cousin to the North American black widow spider which is one of the few species where the male actively aids the female to eat him during copulation [3].

Some globular clusters contain several eclipsing systems. For example, 47 Tuc has at least five black widows and two redbacks, while in Terzan 5, two black widows and three redbacks have been discovered. Observations with HESS of 47 Tuc [4] and with MAGIC of M13, which contains one known black widow [2], have only yielded upper limits. However, globular clusters are fairly distant objects. 47 Tuc is at 4 kpc, Ter 5 is at 5.5 kpc, while M13 is at 7 kpc. Therefore, a single energetic black widow or redback at a distance of 1 kpc could be much brighter than any cluster at TeV energies. For details and references on the globular cluster systems, see P. Freire's webpage.

4 A Field Full of Black Widows and Redbacks

Recent radio surveys designed to be sensitive to very fast pulsars in tight binaries have greatly increased the number of known MSPs in the Galactic field, including the number of black widows and redbacks. Large scale sky surveys with GBT and Parkes

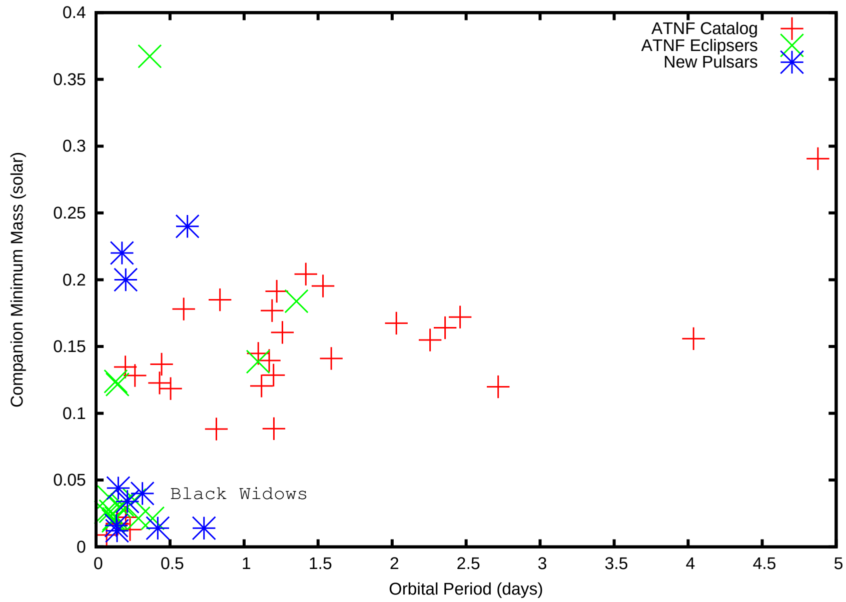

Figure 1: Binary period vs. minimum mass for binary pulsars with spin periods $P < 5$ ms and orbital periods < 5 days in both globular clusters and the Galactic field. The new Galactic field eclipsing pulsars are in blue, the others are from the ATNF Catalog. The black widows form a distinct class in the bottom left of this diagram, while the redbacks tend to the left of the plot.

have so far discovered two new black widows and two new redbacks. One of the most intriguing of the new redbacks, discovered in the GBT drift scan survey, is J1023+0038 [5]. This 1.69 ms eclipsing pulsar is in a 4.8 hr orbit around a $\sim 0.2 M_\odot$ companion. In 2001 the system showed strong evidence in its optical spectrum for an accretion disk, but since 2002 has had the spectral characteristics of an ordinary G star [23]. This suggests the system has been caught in the act of recycling, switching between accreting from its companion and ablating its companion, making the designation of redback particularly apropos in this case. The non-degenerate companion supplies a photon density at the intrabinary shock that is similar to the one the Be-star in PSR B1259−63 supplies in that system near periastron, since the shock should be very close to the companion in J1023+0038. In addition, the $\dot{E}/d^2$ is similar for both system, making this an excellent target for TeV telescopes.

Radio searches of *Fermi* γ-ray error boxes is proving to be a very efficient way of discovering energetic MSPs [19]. As of the time of this talk, 18 MSPs had been discovered by observations with the Parkes, Nancay, and especially the Green Bank Telescopes, including 4 black widows and 1 redback. Since then, roughly 10 more MSPs have been found this way (the number is changing on an almost daily basis) with at least one more new redback. Multi-wavelength follow-up has commenced in a number of cases, with many having identified X-ray and optical counterparts. In addition, VLBI campaigns to determine accurate distances have commenced for several of the brighter sources. It should be noted that so far there is no evidence of orbitally modulated GeV emission in the Fermi data from these sources. In addition, clear γ-ray pulsations have been seen from several of these systems, suggesting much of the GeV emission from these systems is magnetospheric in nature rather than from an intrabinary shock. It should be noted that only weak GeV emission has been seen from PSR B1259−63 during its current periastron passage by *Fermi* [1], and so a strong GeV component to the shock spectrum does not seem to be necessary in order for there to be significant TeV emission from colliding wind systems.

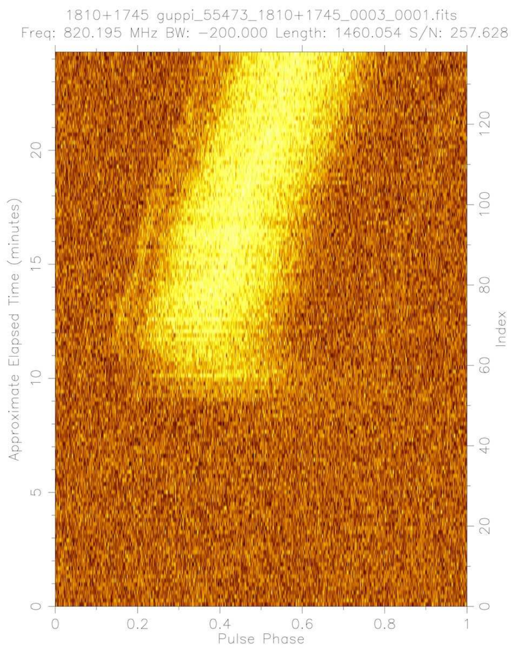

Figure 2: A plot of pulse phase vs. time of PSR J1810+1745 as it comes out of eclipse. The orbital motion is not fully corrected for, but it is still apparent that there is extra delay of the pulse due to scattering near the edge of the eclipse

References

[1] Abdo, A.A., et al. 2010 ATEL #3085

[2] Anderhub, H., et al. 2009, ApJ, 702, 266

[3] Andrade, M.C.B. 1996, Science, 271, 70

[4] Aharonian, F., et al. 2009, A&A, 507, 389

[5] Archibald, A. M., et al. 2009, Science, 324, 1411

[6] Arons, J., & Tavani, M. 1993, ApJ, 403, 249

[7] Chatterjee, S., et al. 2009, ApJ, 698, 250

[8] Cominsky, L., Roberts, M., & Johnston, S. 1994, ApJ, 427, 978

[9] Cordes, J. M., & Lazio, T. J. W. 2002, arXiv:astro-ph/0207156

[10] D'Amico, N., Possenti, A., Manchester, R. N., Sarkissian, J., Lyne, A. G., & Camilo, F. 2001, ApJL, 561, L89

[11] Fruchter, A. S., Stinebring, D. R., & Taylor, J. H. 1988, Nature, 333, 237

[12] Fruchter, A. S., et al. 1990, ApJ, 351, 642

[13] Huang, H. H., & Becker, W. 2007, A&A, 463, L5

[14] Keith, M. J., et al. 2010, MNRAS, 409, 619

[15] Kulkarni, S. R., & Hester, J. J. 1988, Nature, 335, 801

[16] Lorimer, D. R. 2008, Living Reviews in Relativity, 11, 8

[17] Manchester, R. N., Hobbs, G. B., Teoh, A. & Hobbs, M., 2005, AJ, 129, 1993

[18] Raubenheimer, B. C., Brink, C., de Jager, O. C., & Nel, H. I. 1995, ApJ, 444, 419

[19] Ransom, S. M., et al. 2010, arXiv:1012.2862

[20] Stappers, B. W., Gaensler, B. M., Kaspi, V. M., van der Klis, M., & Lewin, W. H. G. 2003, Science, 299, 1372

[21] Tavani, M. 1993, A&AS, 97, 313

[22] Tavani, M., Arons, J., & Kaspi, V. M. 1994, ApJL, 433, L37

[23] Wang, Z., Archibald, A. M., Thorstensen, J. R., Kaspi, V. M., Lorimer, D. R., Stairs, I., & Ransom, S. M. 2009, ApJ, 703, 2017

On TeV Emission From Magnetars

Eric Gotthelf
Columbia University
NY 10027, USA

Abstract

In 2008 I addressed the question of whether magnetars would make good TeV targets for VERITAS and concluded without hesitation that they would not. This assertion was based on a statistical study of the overlap of known magnetars and the HESS Galactic Plane Survey sources. Against all expectations we have now located a magnetar associated with a TeV source. Here, I will first reproduce the original arguments for not observing known magnetars and then present the first magnetar coincident with a TeV source. CXOU J171405.7?381031 is an energetic 3.82 s magnetar that lies within the extent of HESS J1713-381, the TeV source associated with the supernova remnant CTB 37B. While the TeV emission has been attributed to the remnant's shell, it is possibly centrally peaked, and we hypothesize that this particularly young, energetic magnetar may contribute to the HESS source.

Program

Workshop Scientific Program

Friday, May 28, 2010

15:30	*Opening Remarks*	Reshmi Muhkerjee (Barnard College) & Rene Ong (UCLA)

SNRs and PWNe: Latest γ-ray results Chair: Rene Ong

15:45	Recent Results on SNRs and PWNe from Fermi	Liz Hays (GSFC)
16:15	Recent VERITAS results on SNRs and PWNe	Scott Wakely (University of Chicago)
16:45	Spectrum and morphology of Milagro sources	Andrew Smith (University of Maryland)

19:00 Group Dinner

Saturday, May 29, 2010

SNRs and PWNe: Multiwavelength picture Chair: Martin Pohl (Universität Postdam)

9:00	Gamma-ray emission from SNRs	Don Ellison (NSCU)
9:25	Maser-Emitting remnants	John W. Hewitt (GSFC)
9:50	PWNe: a multi-wavelength perspective	Pat Slane (CfA)

10:15 Coffe Break

10:45	PWN modeling	Joseph Gelfand (NYU)
11:10	PWN in gamma-rays	Oleg Kargalstev (University of Florida)
11:35	Discussions	Pat Slane (CfA)

12:00 Lunch Break

Binary systems and other objects Chair: Brian Humensky (University of Chicago)

13:30	Black holes in the Galacy	Charles Dermer (NRL)
13:55	Puzzling gamma-ray binaries from a Fermi perspective	Richard Dubois (SLAC)
14:20	TeV observations of Galactic binary systems with VERITAS	Jamie Holder (University of Delaware)
14:45	Cyg X-3 and other non-Be binaries	Robin Corbet (UMBC/GSFC)

15:10 Coffee Break

15:45	TeV results on Cyg X-3 by MAGIC	Roberta Zanin (IFAE)
16:00	Black widows and other binaries	Mallory Roberts (Eureka Scientific, NRL)
16:15	TeV emission from magnetars	Eric Gotthelf (Columbia University)
16:30	Gamma-ray emission concurrent with the Nova in the symbiotic binary V407 Cygni	Kent Wood (NRL)

17:00 End of Meeting

Participants

Workshop Participants

Aliu, Ester	Barnard College, Columbia University
Bugayov, Slava	Washington University
Butt, Youssaf	CfA
Camilo, Fernando	Columbia University
Chiang, James	SLAC
Cohen, Jamie	GSFC
Corbet, Robin	UMBC/GSFC
Dermer, Charles	NRL
Dubois, Richard	SLAC
Dwarkadas, Vikram	University of Chicago
Ellison, Don	University of North Carolina
Erguin, Tulun	CfA
Errando, Manel	Barnard College, Columbia University
Finnegan, Gary	The University of Utah
Gelfand, Joseph	NYU
Gotthelf, Eric	Columbia University
Grube, Jeff	Adler Planetarium, Chicago
Guenette, Roxanne	McGill University
Gyuk, Geza	Adler Planetarium, Chicago
Hailey, Charles J.	Columbia University
Halpern, Jules	Columbia University
Hays, Liz	GSFL
Hewitt, John W.	GSFC
Holder, Jamie	University of Delaware
HongJun, An	Columbia University
Humensky, Brian	University of Chicago
Kara,Erin	Barnard College, Columbia University
Kargalstev, Oleg	University of Florida
Karlsson, Niklas	Adler Planetarium, Chicago
Loo, Andrew	Columbia University
Majumdar, Pratik	UCLA
McArthur, Brett	Washington University
Mukherjee, Reshmi	Barnard College, Columbia University
Nunez, Paul	University of Utah
Ong, Rene	UCLA
Pohl, Martin	Universität Potsdam & DESY
Roberts, Mallory	Eureka Scientific
Senturk, Gunes	Columbia University
Slane, Patrick	CfA
Smith, Andrew	University of Maryland
Theiling, Mark	Purdue University

Thibadeau, Sarah	Washington University
Varlotta, Angelo	Purdue University
Vivier, Matthieu	University of Delaware
Wakely, Scott	University of Chicago
Weinstein, Amanda	UCLA
Wood, Kent	NRL
Zanin, Roberta	IFAE
Zitzer, Ben	Purdue University

Author Index

Subject Index