Recent VERITAS Results on Supernova Remnants and Pulsar Wind Nebulae

Scott Wakely for the VERITAS Collaboration
THE VERITAS Observatory

- Four 12m-diameter Imaging Atmospheric Cherenkov Telescopes
  - Located at Whipple Observatory Base Camp [1300m asl]
  - Full operations began Fall, 2007
  - ~1000 Hours of Observation time per year (including 200+ hrs in moonlight)
VERITAS Performance

- Energy Range: 100 GeV – >30 TeV
- Energy Resolution: 15-20%
- Angular Resolution: ~ 0.1°, FOV: 3.5°
- Original Point Source Sensitivity: 1% of the Crab in under 50 hrs
  - (5σ detection at 70° elevation)

SUMMER 2009: RELOCATION OF TELESCOPE 1
Substantial Improvement in Sensitivity
1% Crab Source now in under 30 hrs
VERITAS Skymap

29 Sources in 6 Source Classes

tevcat.uchicago.edu
Galactic Sources with VERITAS

• General Observation Strategy:
  – Limited Blind Survey
  – Pointed Observations
  – Both of these have led to detections.

• This talk:
  – Galactic SNR and PWN

Jamie (tomorrow): Binaries and Transients
VERITAS Sky Survey

Location based on material distribution and density of potential TeV γ-ray emitters. Size based on FOV and sensitivity.

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TeV Galactic Workshop
VERITAS Sky Survey II

- 2007-2009, 112 base hrs with 56 hrs of follow-up studies
- Cygnus Region Coverage: $67^\circ < l < 82^\circ$, $-1^\circ < b < 4^\circ$
- 4 pre-defined cut-sets (hard/soft, point-like/extended)
- Depth: <3% Crab above 200 GeV [99% CL] for point-like sources
One Interesting Region

- **Subset of Survey**
  - Hard/Extended cuts

- **TeV J2032+4130**
  - Known source, first detected by HEGRA
  - Possible Associations:
    - MGRO J2031+41
    - 1FGL J2032.2+4127/0FGL J2032.2+4122
  - VERITAS Detection is >5σ at nominal position (no trials)

- **New Source!**
  - VER J2019+407
VER J2019+407

- Early Follow-up candidate
  - Independent data set from Fall 2009 confirms existence of a new source at ~7.5σ.
  - Preliminary Flux level above 1 TeV: ~2-5% Crab
  - Preliminary Extension:
    - ~0.2° Symmetric Gaussian Fit
• Peak in NW corner of G78.2+2.1 (\(\gamma\)-Cygni)
  – Distance \(\approx\) 1.5 – 1.8 kpc
  – Age \(\approx\) 5-10 kyr

• TeV Mechanism?
  – Is it the PWN of Fermi PSR J2021+4026?
    – Is it shock-matter interactions?
      • CO? Lots to the SE, not as much in the NW.
      • Shocked High-velocity cloudlet? Location? Mass?
      • Partial HI shell to NW?
      • Shock overtaking cavity wall?

Ladouceur & Pineault 2008

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Targeted Observations
• Young (~330 yr) shell-type SNR
• VERITAS Detection:
  – 22 hours of data (2007), 8.3 $\sigma$
  – Consistent with point source
  – Index: $2.61 \pm 0.24_{\text{stat}} \pm 0.2_{\text{sys}}$ – no evidence for cutoff
  – Flux (> 1 TeV) ~3.5% Crab

Leptonic Model
B=120 μG, PL (-2.34) + cutoff @ 40 TeV
Dashed Line – Brem
Dotted Line – IC (dominated by FIR)

Hadronic Models
Blue: PL (-2.1) + cutoff @ 10 TeV
Red: PL (-2.3)

Hadronic model is favored, but leptons not ruled out

• Older (~20-30 kyr) radio/x-ray bright SNR
• PWN and likely SNR / MC Interaction (masers)
• Co-Discovery in TeV by VERITAS (2007)
  – 38 hrs, 8.3σ, 3.2% Crab (> 300 GeV)
  – Index: $2.99 \pm 0.38_{\text{stat}} \pm 0.3_{\text{sys}}$
  – Emission is extended $\sim 0.16$ deg.


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IC443 II

- Fermi Observations, 5-50 GeV
  - Location consistent with VERITAS
  - Angular Extent $\sim 0.27$ deg

- Hadronic Model
  - Proton population with broken power law spectrum (70 GeV breakpoint)
  - $10^4$ Solar Masses of target material

G54.1+0.3: Motivations

- “Cousin of the Crab”
  - X-ray jet/torus, IR dust shell
  - Age \( \sim 2900 \) years
  - E-dot = \( 1.2 \times 10^{37} \) erg/s
  - Distance \( \sim 6.2 \) kpc

- Also, Nearby Molecular Cloud:

  Leahy et al. (FCRAO)
G54.1+0.3: Results

- Hint of Signal in 07 Moonlight data.
- 2008 Follow-up yields a $7\sigma$ detection in 36 hours
- Location compatible with pulsar
  - Extension consistent with point source.

- Gamma-ray Spectrum:
  - Flux ($>1$ TeV) $\sim 2.5\%$ Crab
  - Index $\sim 2.4 \pm 0.2_{\text{stat}} \pm 0.3_{\text{sys}}$
  - Efficiency: $\eta_Y = 0.17$

Boomerang/PSR J2229+6114: Motivations

- Energetic pulsar + wind nebula discovered in the error box of source 3EG J2227+6122.
  - Age ~ 10,000 years
  - E-dot = $2.2 \times 10^{37}$ erg/s
  - Distance ~ 800 pc (Kothes et al)
  - Likely part of the larger SNR G106.3+2.7

- On Fermi/LAT Bright Source List

- Emission at ~35 TeV reported by Milagro near former “C4” location
Boomerang/PSR J2229+6114: Results

- Observations made in 2008 resolve TeV emission overlapping the radio shell of G106.3+2.7
  - 7.3σ detection in 33 hours (6.0 post-trials)

- TeV emission is extended
  - Spans a 0.4° x 0.6° region
  - Peak is 0.4° away from PSR
  - Overlaps with region of high CO density

Boomerang/G106.6+2.9: Results II

- Energy Spectrum
  - Integrate over 0.32° radius centered on emission peak
  - Flux above 1 TeV is \( \sim 5\% \) of the Crab Nebula
  - Well fit by pure power law
    - Index \( \sim 2.3 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}} \)

- Consistent within errors with Bednarek and Bartosik PWN Model (J Phys G 31, 2005)

- Extension of spectrum is consistent within errors with Milagro point at 35 TeV
  - Favors hadronic origins?

Future Observation Plans

• Suzaku Observations
  – Two 50 ks exposures awarded in AO5

• Need Maser Measurements
  – How?!
Tycho (G120.1+1.4)

- Remnant of a Type Ia Supernova event of 1572
  - Size: ~8 arcminutes
  - Distance: 2.5 kpc – 5.0 kpc
  - Bright x-ray rims and filaments interpreted as evidence for electrons up to ~10 TeV
  - MWL Expansion Studies suggest entry to Sedov Phase
    - Slower expansion to east possibly due to interactions with molecular cloud
  - Detailed x-ray morphology studies suggest efficient hadronic particle acceleration (Warren et al. 05)
Tycho (G120.1+1.4)

- GeV Observations
  - No Detection by EGRET
  - No 1FGL sources within 3deg

- Past TeV Observations
  - Limits from Whipple, HEGRA, MAGIC
    - Best limit: MAGIC centered pt src: $J(>1\text{ TeV}) < 1.7\% \text{ Crab } [3\sigma]$

- VERITAS Observations
  - 67 hours from 2008 and 2010 (after quality cuts)
  - Mean zenith – 38 deg
Tycho (G120.1+1.4)

• VERITAS Detection!
  – 5.7σ pre-trials, 5σ post-trials (scan over area x2 area of remnant + 2 cut-sets)
  – Peak Significance located close to molecular cloud – possible interaction?
  – No strong statistical evidence for angular extension
  – Flux Level above 1 TeV: ~1% Crab

Smoothed TeV Excess Map

Black – X-Ray (Chandra)
Purple - $^{12}\text{CO}$ Emission (FCRAO)
Summary

• VERITAS has made detections of several galactic objects, including several “new” TeV emitters
  
  – γ-Cygni –
    • New TeV-emitting SNR discovered in sky survey, busy region!
  
  – Cas A
    • Bright young remnant, pointlike detection in VTS and Fermi
    • Hadronic models favored. No clouds!?  
  
  – IC443
    • Classic MC/SNR interaction, extended detections by Fermi, VERITAS
    • Fermi+VERITAS data well-fit by hadronic model
  
  – G54.1+0.3/PSR J1930+1852:
    • High E-dot PWN with possible molecular cloud
    • Detection consistent with point source at pulsar location
  
  – G106.3+2.7 (Boomerang):
    • Extended emission, overlapping CO cloud, well away from PWN
    • If associated with MGRO 2229+611, hadronic origins may be favored.
  
  – Tycho
    • Historical Type Ia, several signs of particle acceleration
    • Weak detection peaks near associated molecular cloud