VERITAS Observations of Starburst Galaxies

The Discovery of VHE Gamma Rays from a Starburst Galaxy

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1 see R.A. Ong et al. (these proceedings) or http://veritas.sao.arizona.edu/conferences/authors?icrc2009

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VERITAS: A Cherenkov Telescope Array

- **Arizona**: ~32° N, ~111° W, 1268 m a.s.l.

- **Four identical telescopes**:
  - \( f/D \sim 1.0; D = 12 \text{ m}; f = 12 \text{ m} \)

- **Mirror Area**: ~106 m²; 350 mirrors

- **Camera**: 499 pixels (0.15°) & 3.5° FoV
  - Readout: Dual-gain; 500 MHz FADC

- **3-level trigger**: ~10% dead time; ~300 Hz

- **Data**: ~750 h / year + 35% in moonlight

- **Metrics**: Studies from ~100 GeV to ~30 TeV
  - Detect (5σ) 1% Crab source in <50 h @zenith
  - Angular resolution: \( r_{68} < 0.1° \)
  - Energy resolution: ~15%

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M 82: A Starburst Galaxy

- M 82 is the prototype starburst galaxy
  - \( \delta \sim 70^\circ \Rightarrow \) Culminates at \( \theta \sim 40^\circ \)
  - \( D \sim 3.9 \) Mpc towards Ursa Major: EBL a non-issue
  - Diameter \( \sim 1' \Rightarrow \) Point-like for VHE \( \gamma \)-ray studies
  - Central SMBH: \(< 3 \times 10^7 \) M\(_{\text{sun}}\); No evidence of an AGN

- M 82 interacting with group of galaxies
  - Over hundreds of millions of years
  - At least 1 major interaction with larger spiral M 81

- Tidal forces \( \Rightarrow \) Active starburst region
  - Diameter \( \sim 1000 \) light years
  - HST \( \Rightarrow \) Contains >200 massive star clusters
    - \( 10^4 - 10^6 \) M\(_{\text{sun}}\); brighter than most in Local Group

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The Starburst Region of M 82

- High star formation rate: \( \sim 10x \) Milky Way
- High supernova rate: \( \sim 0.1 \) to \( \sim 0.3 \) / year
- Cosmic-ray (CR) origin? 100-year old question
  - Preferred theory: SNR & wind-zones of massive stars
- High CR density: \( \sim 100x \) Milky Way
  - Inferred from intense radio-synchrotron emission
- High gas density: \( \sim 150 \) particles / cm\(^3\)
- CR hadrons + gas \( \Rightarrow \) pions \( \Rightarrow \) \( \gamma \)-rays
- CR electrons + ambient photons \( \Rightarrow \) \( \gamma \)-rays
- >60\% of EGRET \( \gamma \)-rays from CR
- HEGRA & Whipple: VHE flux <10\% Crab

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VERITAS Discovery of VHE Gamma-rays

- **VERITAS (2007-09): ~137 h live time**
  - Only in astronomical darkness; Mean $\theta \sim 39^\circ$
  - Bad weather data removed (via FIR data)

- **Standard VERITAS analysis + “hard cuts”**
  - $E_{th} \sim 700$ GeV; NB: Sensitivity less at $\theta \sim 39^\circ$
  - Cuts *a priori* optimized using Crab at $\theta \sim 40^\circ$
    - For detection of weak, hard-spectrum sources
      - Theoretical expectation for M 82
  - Standard practice, but 3 trials: “std” & “soft” cuts

- **Point-like excess of 91 $\gamma$; 5.0$\sigma$ pre-trials**

- **Post-trials significance of 4.8$\sigma$**
  - Chance probability of $7.7 \times 10^{-7}$
M 82: A Steady VHE Flux

- Among weakest-ever VHE sources
  - $F(>700 \text{ GeV}) = (3.7 \pm 0.8_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$
    - $0.9\%$ of Crab Nebula ($>700 \text{ GeV}$)
    - Gamma-ray rate: 0.7 / hour

- No variations in monthly flux
  - $\chi^2 = 11.5$, 9 d.o.f.; $P(\chi^2) = 0.24$
  - Factor of "a few" variations not ruled out

- Steady signal accumulation

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Systematic Checks

- All hardware operating normally, no moonlight data & dark NSB region
- "Hard cuts": Enormous images (>200 PE); bright star effects mitigated; very low background (S/N ~ 1/3)
- Result verified (5.2σ) by independent analysis/calibration/simulation package(s)
- Alternate background estimation: Ring method => 5.1σ on-source
  - Also ~5σ using a binned maximum-likelihood method
  - Reflected-region BG method always has 11 off-source regions
  - Significance distribution is Gaussian (mean 0, σ = 1)
- No bias in long data set: Stack extragalactic non-blazar data
  - With the same analysis: Combined excess of -4 events (-0.2σ) in ~121 h of live-time (no moonlight data)
- Not due to brightness of M 82 (V=9.3) when integrated over its extent => V ~ 8.2
  - Two V < 9 stars in FOV: Excesses of 1.1σ & 0.8σ at their locations (>0.7º from M 82)
- Not due to dodgy behavior in a telescope: Signal still present when each tel. is individually excluded
The VHE Gamma-Ray Spectrum

- **Fit Range:** 875 GeV to ~5 TeV
  - Fit to $dN/dE \sim (E / \text{TeV})^{-\Gamma}$
  - $\chi^2 = 0.1$, 1 NDF; $P(\chi^2) = 0.7$
- $\Gamma = 2.5 \pm 0.6$
- **VHE flux close to predictions**
  - Incl. both leptonic & hadronic channels
    - Pohl 1994
    - Völk et al. 1996
    - Persic et al. 2008
    - de Cea del Pozo et al. 2009

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Some Quick Interpretation

• **Leptons or hadrons?**  *We can’t say, yet....*

• **Hadronic channel:** Protons + Matter => Pions => γ-rays; but also => Pions => Secondary Electrons
  
  • Use radio emission from secondary electrons to limit γ-ray flux from CR hadrons @ 20 GeV
  
  • Extrapolate VERITAS spectrum downwards: Γ = 2.5 => Flux ~2x higher; Γ = 2.3 => OK
  
  • **Either the true gamma-ray spectrum from 10 GeV to 1 TeV is “harder” than the VERITAS measurement, or the VHE flux is not predominantly from CR hadrons**

• **Leptonic channel:** CR electrons + ambient photons => X-rays & γ-rays via IC scattering
  
  • Use non-thermal X-ray flux => limit number of electrons @ 1 GeV, but need 10 TeV electrons for VHE
  
  • Theory & comparison to CR-induced X-ray flux to VHE flux => IC spectrum: Γ ~ 2 from 100 keV to 100 GeV
    
    • Electron energy losses (IC & synchrotron) => Steepening + cut-off in IC spectrum above some energy
    
    • If Fermi sees a cut-off, the particles responsible for VHE γ-rays could be identified

• **Dark Matter annihilation?** In concentrations near the central SMBH, or from formation of an identified IMBH
  
  • HESS didn’t see DM-related γ-rays from the GC, or from IMBH’s in Galactic Plane & M 82 is far more distant!
Conclusions

• Enormous VERITAS exposure on M 82: \(~137\) h quality-selected live time over 2 years

• VERITAS has detected M 82 (91 \(\gamma\), 4.8\(\sigma\) post-trials, \(P \sim 7.7 \times 10^{-7}\));
  • The observed flux is steady: \(F(>700 \text{ GeV}) = (3.7 \pm 0.8_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}\); \(\sim 0.9\%\) Crab
  • Luminosity is \(\sim 2 \times 10^{32} \text{ W}\); Approximately 0.03\% of the optical luminosity
  • The observed photon spectrum has large errors: \(\Gamma = 2.5 \pm 0.6_{\text{stat}} \pm 0.2_{\text{syst}}\)

• 1st VHE \(\gamma\)-ray detection of an object that is not clearly related to an AGN

• Measurement of CRs outside the galaxy => Help solve 100-yr old mystery of CR origin
  • VHE detection confirms a long standing prediction of the theory of CR acceleration in SNR

• Detection helps address a number of scientific questions:
  • Role of CRs: in driving large-scale galactic winds; in feedback of star formation on the structure of galaxies
  • Whether smaller shocks (e.g. in SNR) are the predominant CR acceleration sites?
    • or, if CR acceleration occurs on larger scales (>30 ly) in a more distributed fashion?