The Extragalactic Sky in TeV Gamma Rays

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Outline

- Overview of extragalactic TeV sources.
- Discovery of starburst galaxies.
- Probing relativistic jets in TeV blazars.
- Intermediate BL Lac objects.
- Cosmology with blazars.
- Quantum gravity tests.
- Radio galaxies.
- Summary.
Science Motivations:

Radio galaxies: 

GRBs: Jets -

EBL in IR

Blazars: Jets

Dark Matter

...?

Starburst galaxies -

Starburst galaxies -

Science Motivations:

Dark Matter

Hadrons

Blazars: Jets

Unidentified GRBs: Jets - EBL in IR

Radio galaxies: Jets

Starburst galaxies -

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### Recent additions:

- M82, NGC253 starburst galaxies
- Centaurus A, 3C66B radio galaxies
- PKS1424+240, S5 0716+714, RGB 0710+591 blazars
- LMC Pulsar wind nebula outside Milky Way

**TeVCAT: Courtesy: S. Wakely, UChicago**
Starburst Galaxies: M82

- M82 is the prototype starburst galaxy
- Distance ~ 3.9 Mpc
- Diameter ~ 1’
- SMBH ~ $3 \times 10^7$ $M_{\text{solar}}$
- Interacts with group of galaxies (M81)
- HST: 200 massive star clusters
- High supernova rate ~ 0.1 - 0.3 per year
- High gas density 150 particles/cm$^3$

-> excellent candidate for cosmic ray interactions & gamma ray emission.

-> probing paradigm that SNRs are the origin of C.R.s.
Starburst Galaxies: M82

- **VERITAS data ~ 137 h livetime**
  
  only astronomical dark time, large zenith angle ~ 39°
  
  increased $E_{\text{thres}}$
  
  bad weather removed

- **Standard VERITAS analysis (“hard cuts”)**
  
  $E_{\text{thres}} \sim 700$ GeV
  
  cuts a priori optimized on Crab
  
  hard spectrum expected from theory
  
  but we count for 3 trials (standard, hard & soft)

- **Point-like excess of 91 $\gamma$; 5.0 $\sigma$ (pre-trial)**
  
  3 independent analyses
  
  many systematic checks performed

- **Post-trial: 4.8 $\sigma$ ($7.7 \times 10^{-7}$)**
  
  steady signal
  
  excess consistent with instrument PSF

- **M82 weakest source ever detected @ VHE**
  
  0.9% of Crab
  
  Gamma-ray rate: 0.7 $\gamma$/hour

**Acciari et al. 2009, subm. to Nature**
Starburst Galaxies: M82

- Spectrum 875 GeV to 5 TeV
- \( \frac{dN}{dE} \sim (E / \text{TeV})^{-\Gamma} \)
  \[ \Gamma = 2.5 \pm 0.6 \]
- VHE flux is close to predictions incl. leptonic & hadronic channels
- Origin: hadronic or leptonic?

\[ pp \rightarrow \pi^0 \rightarrow \gamma \gamma \]
\[ pp \rightarrow \pi^\pm \rightarrow e^\pm \ldots \]

radio

20 GeV with \( \Gamma = 2.3 \), TeV flux OK.

\[ e^- \quad \rightarrow \gamma \quad \text{synchr.} \]
\[ e^\gamma_{\text{soft}} \rightarrow \gamma \quad \text{TeV} \]

cutoff

Sensitivity < 1 mCrab needed
VERITAS: pathfinder for next generation instruments such as AGIS, CTA

Acciari et al. 2009, subm. to Nature
Relativistic Jets in Blazars

- "Standard Model" of AGN Physics
  SMBH
  Accretion disk
  Relativistic jet

- Point of view changes appearance
  Blazar
  Quasar
  Radio galaxy

- Physics questions
  Black hole - jet - connection
  Acceleration mechanism
  Emission mechanism
  Maximum energy
  hadrons and leptons?
  UHE cosmic ray connection?
  Axion emission?
PKS 2155-304

- **HBL at z ~ 0.116**
  EGRET source
detected by HESS

- **“Gigantic” flare ~ 11 Crab**
  HESS: 6.5 hrs of observations July 29-30 2006
  ~ 30,000 photons
  Chandra observations 30 ks
  emission dominated in TeV regime

- **TeV/X-ray correlation**
  contemporaneous coverage
  correlation, no time lags
  amplitude of variations ~ 22 (TeV),
  ~ 2 (X-ray),
  ~ 1.15 (optical)
cubic relation between TeV/X-ray variations

- **One-zone SSC Model**
inconsistent with one zone modell

- **Conclusions**
Compton dominated emission component
inconsistent with one-zone SSC

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PKS 2155-304 with Fermi+HESS

- **HESS**, Fermi, RXTE, optical
  
  11 days, Aug. 2008
  
  low flux state, but detectable

- **SED optical, X-ray, GeV - TeV**
  
  nightly flux variations in optical, X-ray, TeV
  
  power comparable in X-ray, GeV, TeV
  
  TeV/optical correlate
  
  TeV/X-ray do not!

- **Interpretation**
  
  one-zone SSC model
  
  X-ray synchrotron from high energy electrons
  
  -> IC scattering in Klein Nishina regime
  
  -> TeV emission not changed
  
  optical synchr. emission from low E electrons
  
  -> TeV and optical emission correlated
  
  -> GeV emission should also correlate but does not!
  
  one-zone SSC models can explain SED but not the variability pattern!
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Intermediate BL Lacs

**LBL:**
powerful, substantial external radiation fields

**IBL:** fall between

**HBL:**
low power, weak external radiation fields

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W Comae

- **IBL (intermediate BL Lac)**
  - discovered in radio (X-rays), 1971 (1980)
  - seen by EGRET: 0.1 - 10 GeV
  - $z = 0.102$
  - promising candidate for TeV

- **VERITAS discovery of TeV emission**
  - $4.9 \sigma$ in 40 hours
  - outburst March 2008 (> $8 \sigma$ detection)
  - quasi-simultaneous X-ray data

$\sigma_t = 1.29 \pm 0.28$ days
W Comae

- **One-zone SSC**
  weak magnetic field
- **External Compton**
  $B \sim 0.3$ Gauss
- **GeV - TeV coverage**
  distinguish between the two

3C66A

- **IBL**
  seen by EGRET and Fermi (#1759)
z = 0.44 (highly uncertain)
promising candidate for TeV
Crimean group reported 5.1 σ at 1 TeV (1996-98)

- **VERITAS detects TeV emission**
  21 σ in 33 hours, ~ 1800 γ; $E_{\text{thres}} \sim 120$ GeV

- **MAGIC detects 3C66B (radio galaxy)**
at 0.12 degree off-set from 3C66A (not contemp.)

- **Two sources or just one?**
data is not contemporaneous!
VERITAS detection is unambiguously 3C66A
3C66A: Fermi & VERITAS

- **Fermi data**
  Sept. 1 - Dec. 31 2008
  0.1° x 0.1° pixel map
  Fermi & VERITAS identify 3C66A
  Fermi cannot exclude small contribution from 3C66B

- **PAIRTEL/Chandra/Swift/VERITAS**
  SED peaks in GeV regime

- **SED modeling**
  one-zone SSC model
  EC+SSC
  high ambient seed population in IBLs
  target for IC scattering

PKS 1424+240

- **IBL detected by Fermi**
  0.2 - 100 GeV
  $\Gamma = 1.8 \pm 0.07$
  promising target for IACTs
  Fermi & VERITAS identify 3C66A
  Fermi cannot exclude small contribution from 3C66B

- **TeV emission discovered by VERITAS**
  no evidence for variability
  7.5 $\sigma$ in full data set

- **First TeV discovery motivated by Fermi**
  $E > 1$ GeV useful to find new TeV blazars with IACTs

- **IBLs: strong link between Fermi/IACTs**
  promising for many more GeV-TeV spectra
  AGN population studies
  EBL studies (UV-optical-near IR)
Population Studies

• **Blazar discovery program**
  
  X-ray selected BL Lacs
  
  ~ 60 blazars observed
  
  excluded detections
  
  remaining objects stacked (120 hours)

• **Combined excess of 49 blazars**
  
  ~ 4.8 $\sigma$
  
  480 events

Physics: EBL/Cosmology

- probe diffuse Cosmic IR-Background
- EBL poorly understood: near - mid IR
- TeV beam: $\gamma + \gamma \rightarrow e^+ + e^-$ interaction
- measure CIRB: absorption$(z)$

Star/galaxy Formation $z<5$
AGNs $z<5$
First stars $z \sim 7 - 30$
Relics?
Truly diffuse Component?

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Upper Limits - Blazar spectra

- Hard spectra blazars exhibit unusually hard spectra for given $z$ (0.12 - 0.22) intrinsic spectra by considering EBL lower limits
- $\Gamma \sim 1.5$ already reached by combining lower limits
- $\Gamma = 1.5$ not a speed limit, or new physics?


Aharonian et al. 2006, Nature, 440, 1018


1ES0347-121
1ES1101-232
1ES1218+30.4
H2356-309
1ES0229+200
1ES0229+200
RGB J0710+591

$\Gamma_{\text{obs}} \sim 2.5 - 3.1$
“Time of flight” test: $c = \text{const}$?

\[ t_1 = \frac{L}{c} \left[ 1 - \frac{E_1}{E_{QG}} \right] \]
\[ t_2 = \frac{L}{c} \]

\[ \Delta t \approx \left( \frac{L}{c} \right) \left( \frac{E}{E_{QG}} \right) \]

$E_{QG} > 7.2 \times 10^{17} \text{ GeV}$

PKS2155-304


Biller et al. 1999, PRL, 83, 2108

Whipple Collab.

Abdo et al. 2009, Science, 323, 1688

Fermi Collab.


MAGIC Collab.
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PKS2155-304 no dispersion!

\[ E_{QG} > 7.2 \times 10^{17} \text{ GeV} \]

Abdo et al. 2009, Science, 323, 1688
Fermi Collab.

Biller et al. 1999, PRL, 83, 2108
Whipple Collab.

HESS: Aharonian et al. 2008,
PRL, 101.170402
HESS

MAGIC Collab.

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Radio Galaxies: M87

- Nearby giant radio galaxy, 16 Mpc
  SMBH $\sim 6 \times 10^9 M_{\odot}$
  Jet angle $\sim 15 - 30$ deg. (not a blazar)
  resolved jet (radio, optical X-ray)
  variable emission

- TeV emission
  Evidence in Hega data
  Confirmed by HESS, MAGIC, VERITAS
  angular resolution of TeV instruments 0.1 deg.
  TeV emission from where?

Radio Galaxies: M87

80 kpc $\sim 0.3$ deg.

radio (43 GHz, VLBA)

X-ray (Chandra)

optical (V band)

radio (6 cm)
Radio Galaxies: M87

- **Joint TeV campaign:**
  MAGIC, HESS, VERITAS
  Jan. - May 2008
  95 hrs. combined
  MAGIC ToO

- **VLBA movies**
  14 shots in 2008, every 5 days
  ang. resolution 0.2 x 0.4 mas

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**A**

VHE instruments
- • VERITAS
- • MAGIC
- • HESS

Time vs. \( \Phi_{VHE} \) [10^{-12} cm^{-2} s^{-1}]

**B**

\( \Phi_{VHE} \) [10^{-12} cm^{-2} s^{-1}]

**C**

\( \Phi_{[43 \text{ GHz}]} \) [Jy]

- • nucleus (r = 1.2 mas)
- • peak flux
- • jet w/o nucleus (1.5-5 mas)
Radio Galaxies: M87

- **Picture?**
  - radio, X-ray and TeV flare are likely related ($P < 0.5\%$).
  - TeV flares on time scales of 1 day: ~ few $R_s$
  - X-ray quiet at HST-1, but shows a historically high state for core.
  - VLBA flare at core ($30 \times 60 \ R_s$), but slow rise.

- **What does this mean?**
  - Model:
    - we have observed plasma traveling down the jet.
    - transparent at TeV and X-ray energies.
    - region is initially opaque in radio (synchr. Self-absorption).
    - and smoothen the radio flare and a delay in peak.
    - TeV/X-ray emission region well within radio blob.

- TeV emission produced close to the SMBH?

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Other Radio Galaxies

- Centaurus A
- Closest active radio galaxy, 3.8 Mpc
  Detection by HESS, & Fermi 5 $\sigma$
  future multiwavelength coverage: radio, optical, X-ray

- 3C66B?
- $\sim$ 80 Mpc
  Detection by MAGIC 5.4 $\sigma$
  but location is within 2 $\sigma$ of 3C66A
  open question!

Summary

- TeV $\gamma$-ray observations provide a window to extragalactic astronomy at the highest energies with $> 30$ sources.
- Study of cosmic accelerators: relativistic jets, BH-jet connection, …
- Fermi + IACTs are promising to constrain models.
- Probe cosmological radiation fields and Lorentz invariance.
- Discovery of starburst galaxies: role of supernovae in cosmic-ray accel.
- AGIS/CTA is the natural next step following Fermi & present IACTs.