Status of TeV AGN Studies

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The Extragalactic VHE Gamma-ray Sky

- May 1, 2011: 122 sources in TeVCat
  - Flux range: 0.003 Crab to ~20 Crab flare
  - ~8 different source classes
  - Systematics: $\Delta \Gamma \sim 0.1$, Flux ~20%
- 47 extragalactic VHE sources (45 AGN)
  - 2 starburst galaxies: M 82 & NGC 253
  - 4 radio galaxies: 3 FR I & IC 310
  - 41 blazars (c.f. 3EG catalog = 66)
    - 73% are HBL (30 objects)
    - 11 non-HBL: 3 LBL, 5 IBL & 3 FSRQ
- $z$ range: 0.030 to at least 0.536

3 blazars (2 IBL, 1 HBL) in same FoV!

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30 HBLs: The Bread & Butter of VHE AGN

- Spectral range: $\Gamma \sim 2.5$ to $\sim 4.6$; Avg $\sim 3.5$
- Highest E photons: $\sim$20 TeV (Mkn 421/501)
  - Mkn 421 / 501 $E_{\text{cut}}$ @ $E_c \sim 4 / 6$ TeV, PKS 2155: $\Gamma \sim 3.5$
- 60% show some variability, but often weak
  - 5 detected (few % Crab) only during brief flares
  - 5 w/ weak, month-scale variations; 2-3% Crab sources
  - 3 have 1-day factor of few flares; in otherwise steady, moderate flux (few % Crab) data
- Only 10 are “well-studied”
- Only 5 w/ long, day-scale flaring episodes
  - These are the five brightest!
- $\sim$2% Crab limits exist for $>100$ AGN
  - Initially: Bright HBL (& IBL); Now Hard LAT $\Gamma$ blazar

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Significant (5$\sigma$) stacked excess for X-ray selected (HBL/IBL), but not LAT-selected, blazars
Modeling VHE HBL Emission

- VHE blazar papers since ~2008 all have simultaneous MWL SEDs for modeling
  - Swift, LAT, Chandra, RXTE, XMM + optical & radio
- HBL: modeling 1-zone SSC works well
- SSC model parameters:
  - Size of emission region: $R \sim 10^{15}$ cm (~100 AU)
  - Homogeneous magnetic field: $\sim 0.1$ G
  - Doppler factor: $\delta \sim 10 - 20$
  - Electron distribution:
    - Broken ($\gamma_{\text{break}}$) power-law, between $\gamma_{\text{min}}$ & $\gamma_{\text{max}}$
    - Normalization $\sim 10^4$ cm$^{-3}$, $n_1 \sim 2$, $n_2 \sim 3.5$
    - $\gamma_{\text{min}} \sim 10^3$, $\gamma_{\text{max}} \sim 10^6$, $\gamma_{\text{break}} \sim 10^5$
- SSC model works during HBL flares (usually)
Modeling the Mkn 421 Flaring in 2008


SSC works in all flare states for Mkn 421 even with factor of ~10 variations over long periods of time

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Extreme Contrast: Mkn 501

1997 Flare

2009 low state

Synch. peak moves by 2 orders of mag.

VHE peak moves little:
Onset of Klein-Nishina effects

SSC scenario successfully models both states:
Transition largely due to change in electron distribution
The Five IBLs: An EC component needed?

- SSC + EC preferred pure SSC for 3 of 4
  - Exception is PKS 1424+240; B2 1215+30 result too new
- W Com \((z = 0.102; \nu_{\text{peak}} \sim 10^{14.8})\): 2 flares in ’08
  - Flare #1: ApJ, 684, L73, 2008; \~9\% Crab; \(\Gamma = 3.8 \pm 0.4\)
  - Flare #2: ApJ, 707, 612, 2009; \~25\% Crab; \(\Gamma = 3.7 \pm 0.2\)
- 3C 66A \((z \text{ ?}; \nu_{\text{peak}} \sim 10^{15.6})\): VERITAS flare in ’09
  - \~6\% Crab; \(\Gamma = 4.1 \pm 0.4\); Day-scale (2x) flare \(\Gamma\) steady
- 1ES 1440+122 \((z = 0.162; \nu_{\text{peak}} \sim 10^{16.5})\): \~1\% Crab
  - VERITAS ATel #2786; \(\Gamma \sim 3.4\)
- PKS 1424+240 \((z \text{ ?}; \nu_{\text{peak}} \sim 10^{15.7})\): Steady flux?
  - VERITAS: ApJ, 708, L100, 2010: 5\% Crab; \(\Gamma = 3.8 \pm 0.5\)
  - MAGIC: High state in ’09?; VERITAS flux lower in ’11
- B2 1215+30 \((z = ?; \nu_{\text{peak}} \sim 10^{15.6})\): MAGIC ATel #3100;
  - 2\% Crab in 4-day optical flare; early days.....
  - VERITAS >6\(\sigma\) in 2008-11 (~55 h data): \~1\% Crab
  - VERITAS detects low-states now (\(t \sim 50\) h)

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The Three VHE LBLs: Much to Learn

- BL Lac & S5 0716+714 detected only during VHE flares simultaneous to optical high state
- BL Lac ($z = 0.069; \nu_{\text{peak}} \sim 10^{14.3}$)
  - MAGIC Flare in 2005: $\sim 5\sigma$ in 22 h; 3\% Crab; $\Gamma = 3.6 \pm 0.5$
  - Many UL below '05 flux: MAGIC in '06 (25 h), VERITAS in '10 ($\sim 10$ h), strong limits prior to '05
- S5 0716+714 ($z = 0.31?; \nu_{\text{peak}} \sim 10^{14.5}$)
  - MAGIC Flare in 2008: $\sim 6\sigma$ in 13 h; 9\% Crab; $\Gamma = 3.5 \pm 0.5$
  - '07 MAGIC “flux” $\sim 9\times$ less; VERITAS UL in '11 ($\sim 10$ h)
- AP Lib ($z = 0.049; \nu_{\text{peak}}$ is $?$, but Swift $\Gamma = 1.5$)
  - Not variable in VHE or LAT; ATel #2743 & Texas Symp. pres.
  - HESS 2010: $\sim 6\sigma$ in 8 h; 2\% Crab; $\Gamma = 2.5 \pm 0.2$
  - Simultaneous LAT $\Gamma$ extrapolates smoothly to VHE
  - IC peak $\sim 2\times$ wider than synch. peak
FSRQs: Brief VHE Emitters

• 3C 279 (z = 0.536): MAGIC 2x 1-day flares
  • Feb 23, 2006: 6.2σ (pre-trials), 80% Crab; Γ = 4.1 ± 0.7
  • Science, 320, 1752, 2008: Most-distant VHE source
  • No MAGIC signal in 30 h from 2007-09, but:
    • Jan 16, 2007: 5.6σ (pre-trials); 10% Crab, Γ = 3.1 ± 1.1
  • Flares during high optical/X-ray states

• PKS 1222+21 (z = 0.432): 30-min flare
  • MAGIC: June 17, 2010: 10σ, 70% Crab; Γ = 3.8 ± 0.3
  • Contemp. LAT data seem to “connect”; Fast variability

• PKS 1510-089: HESS detects in long exp.
  • HEAD 2011 presentation: Few details since

• Emission seems problematic for 1-zone (SSC or SSC+EC) models;
  • Outside BLR? 2-zone? lepto-hadronic?
VHE Blazar Flaring: An Overview

Only 4 VHE blazars (1ES 1959+650, PKS 2155, +) have ever been observed >1 Crab; Only 2 (Mrk 501 +) w/ more than one episode & only Mrk 421 >2 Crab more than once

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“Common Knowledge” about Flaring HBL

- Illustrative case using Mkn 421 in 2008
  - Same trends seen in long-term studies
  - Similar results seen for a few other VHE HBL
- VHE spectral hardening w/ increased flux
- X-ray & VHE fluxes are linearly correlated
  - VHE/X-ray spectral hardening also correlated
- Low “flicker” states: No correlation seen; or VHE correlation w/ optical & not X-ray
4 Most Extreme Flares w/ 3rd Generation

PKS 2155-304 (90 min) & Mkn 501 on Same Scales

HESS: PKS 2155-304 (7/28/06)
MAGIC: Mkn 501 (7/9/05)

1 min bins
1-3 minute variability
No MWL

VERITAS: ~5 h Exposure on Mkn 421

2 min bins
5-10 minute variability
No MWL

HESS: PKS 2155-304 Flare on 7/30/06
7.5 h of data - ~6 h Simultaneous w/ Chandra

2 min bins
Hour-scale variability
20 min. episodes


Taken from Hinton 2007
The Big Flare of PKS 2155-304 (z = 0.116)

- 9-yrs HESS monitoring: 4 nights >2 Crab
- 90 min. episode: Factor of 23 flux range
  - ~12000 $\gamma$, 168$\sigma$, $\gamma$-rate: 2.5 Hz (after cuts)
  - $F_{\text{var}} = 0.58 \pm 0.03$; ~2x higher than X-ray
- Almost no spectral change from low state, despite factor of ~50 flux change
- 5 bursts; Fit GRB “generalized Gaussian”
  - Best $\tau_r = 173 \pm 28$ s; Fastest $\tau_r = 67 \pm 44$ s
    - Best: $R < \delta \times 4.7 \times 10^{12}$ cm $< \delta \times 0.31$ AU
- BH is $\sim 10^9 M_{\text{sun}}$: $\delta > \sim 100$ $R / R_{\text{sch}}$
  - Energetics + VHE photon escape: $\Gamma > 50$
- GRB like Doppler factors or variability not related to black hole
Big Flare: X-ray Timing Techniques

- PDS: Significant power down to 600 s

- $P \sim \nu^{-2}$ (red-noise like)
  - $\nu^{-1}$ rejected; Too much power at high-$\nu$
  - Remarkably similar to X-ray power spectra

- Log-normal process suggests multiplicative (not additive) process

- Typically related to undamped fluctuations in accretion rate
  - Scenarios of binary BH system proposed
  - Tidal disruption of massive object? e.g SwJ1644?

- Alternative fast moving jet w/ several compact (faster moving) sources
  - Simple SSC explanation
  - Larger component dominates “steady state”

No sign of high-$\nu$ cutoff suggests even faster variability may be detectable with a more sensitive instrument

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PKS 2155-304: Chandra Flare Highlights

- ~7.5 h HESS exposure, 6 h w/ Chandra
  - Brighter, but slower (~1 h) than “fast flare”
- Changes: 20x VHE, 2x X-ray, 15% optical
  - VHE/X-ray harder when brighter
  - VHE spectra more curved with higher flux
  - Synchrotron & inverse-Compton peaks don’t move
- X-ray/VHE flux correlation strong & cubic
  - No lags between bands or within bands
  - VHE/X-ray spectra correlated; similar time evolution
- No optical corr. aside from rise at flare onset
- Extremely Compton-dominated (10x) flare
  - Never seen before
- Again, multiple SSC components needed

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More Lessons from PKS 2155-304

Quiescent State is seen (15% Crab)

Spectral evolution is perhaps a bit more complicated than harder vs brighter


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VHE Blazars & Extragalactic Background Light

- **Diffuse EBL**: Analogous to CMB; Combined flux of all extragalactic sources over entire history of Universe

- **EBL absorbs γ's**: $F_{\text{int}} = F_0 e^{-\tau(E, z)}$
  - Softens VHE spectra; eventual VHE horizon

- **Constrain w/ “distant”, hard $\Gamma$ VHE blazars**
  - Assume $\Gamma_{\text{int}} > 1.5 \Rightarrow$ How high can EBL be?
  - 1ES 1101-232 ($z = 0.186$): $\Gamma_{\text{obs}} \sim 2.9$; Best limits from 0.2 to 2 $\mu$m; Nature, 440, 1018, 2006
  - 1ES 0229+200 ($z = 0.139$): $\Gamma_{\text{obs}} \sim 2.5$; up to 10 TeV; Best limits from 2 to 20 $\mu$m
  - Several other hard ($\Gamma_{\text{obs}} \sim 3.1$) VHE HBL (e.g. 1ES 1218+304, 1ES 0347-121); limits within 20% of best
    - PG 1553+113: $z > 0.43$; May result in best yet....
    - How to increase limits: Produce $\Gamma_{\text{int}} < 1.5$; Outer jets?
  - 1ES 1218+304 ($z = 0.182$; $\Gamma_{\text{obs}} \sim 3.1$): VHE flare rules out steady-state models that “refute” EBL limits
**Major Blazar Efforts in the Near Future**

Major annual MWL (incl. all VHE) efforts organized for: Mkn 421 & Mkn 501

Simultaneous X-ray & VHE every 2-3 days; LAT is always on; + optical/radio

Mkn 421 in 2010
6 papers in the works

VERITAS deep 6-year campaigns on 14 blazars (100-200 h shots on HBL, IBL, LBL) + LAT + X-ray/optical/radio

Mkn 501 in 2009:
M 87: The Best VHE Radio Galaxy


- 2005: HESS detects variable, point-like, hard-spectrum excess from the core

- Only other 3 too faint: Cen A (5σ in >100 h), NGC 1275 & IC 310: ~5σ in 1-day flares

M87 -- From 200,000 Light-Years to 0.2 Light-Year

VERITAS, MAGIC, HESS, others, in prep.

M87: HESS day-scale variability in 2005
Science, 314, 1424, 2006

d ~16 kpc
M_{BH} ~ 6 \times 10^{9} M_{\text{sun}}
Jet angle ~ 20º
M 87: The 2008 Flare

VHE flaring along with simultaneous birth of radio-knot & nuclear X-ray flare

Strongly suggests core as a source of VHE emission!

Acciari et al., Science, 325, 444, 2009
M 87: The 2010 Flare

- Sub-day-scale variability (0.6 days)
  - $R < \delta \times 10^{15} \text{ cm}; R_s = 1.8 \times 10^{15} \text{ cm}; 10^{15} \text{ cm} = 67 \text{ AU}$
  - Coincides w/ X-ray (Chandra) core brightening again, but no radio core brightening
  - VERITAS: Significant (3.4$\sigma$) spectral changes
  
  - Peak $\Gamma \sim 2.19 \pm 0.07$ vs Decay $\Gamma \sim 2.62 \pm 0.18$
Conclusions

• 45 VHE AGN: ~70% HBL, but growing pop. of IBL, LBL, FSRQs & Radio Galaxies
  • Non HBL largely detected during flares; 60% of HBL show some variability
  • Extreme variability is very rare: Only a few major events in past decade

• Modeling of HBL w/ SSC is successful; Even during “slow” flares
  • Non-HBL requires SSC+EC or more complex; Extreme variability also more complex

• Future of 3rd Generation: AGN source count will probably be close to EGRET (67)
  • Deep (~200 h @ VHE) MWL campaigns on ~20 AGN: Dduty cycle, low states for IBL/LBL, long MWL corr. studies
    • Probably get a 5σ measure of EBL & some strong constraints on IGMF

• What can CTA bring us? Source counts nearer to ~1000; Larger population of non-HBL
  • Population studies; May detect low states of LBL & FSRQ; Perhaps pick up flickering in strong IBL & weak HBL
  • HBL variability: What was annual can be nightly, nightly can be hourly, minute-scale can be second-scale
  • Currently best spectral variability done on 5-10 minute scales; Down to 30-second scales
  • Easy detections beyond 10 TeV: EBL, IGMF, UHECR implications; Troubles for SSC?
Orphan Flare of 1ES 1959+650

- Nearby VHE blazar (HBL) well-studied since 1998
- Except for 2002 outburst, no flux variations $>2x$ seen
- June 4, 2002: “Orphan flare”: VHE bright & X-ray low
  - Challenges 1-zone SSC model; Hadronic?
  - Tagliaferri et al. 2008: X-ray varies by $\sim2x$; but VHE flux same; SSC ok
- Interesting, but not significant, AMANDA neutrino result
  - Implies hadronic process, but trials impossible to calculate
VHE Flares & Lorentz Invariance Violation

- Quantum gravity & effective field theory: possible energy dependence in $c$
  - Small effect; Linear or quadratic in $E$
  - Near Planck energy: $E_P = 1.22 \times 10^{19}$ GeV
- Detectable for cosmological sources
  - Flaring-AGN / GRBs: High-$E$ photons lag lower-$E$
  - Result assumes photons emitted at same time
- Best VHE result: PKS 2155-304 flare
  - Others: Mkn 421 (Whipple) & Mkn 501 (MAGIC)
- No delay $\Rightarrow$ Linear effect at $E > 6\% \ E_P$
- NB: Fermi-GRB: 31 GeV $\gamma < 1$ s late
  - $E > few \ M_P$; Nature, 462, 331, 2009

$\tau_{\text{peak}} = 20$ s, RMS of $\tau_{\text{peak}} = 28$ s; 21% of $\tau_{\text{peak}} < 0$ s