Radio Galaxies @ Highest Energies: On M87 and Cen A

Frank M. Rieger

FAA60
Barcelona, Nov. 7th, 2012
_Warm-up
  ▶ Radio galaxy at HE and VHE

_Radio galaxies @ VHE
  ▶ Status and Characteristics

_Variable VHE in M87 - theoretical interpretations
  ▶ Overview
    ▶ Magnetospheric VHE emission & jet formation

_UHE cosmic rays in Cen A
  ▶ What to expect?
“...the wide variety of AGN phenomena we see is due to a combination of real differences in a small number of physical parameters (like luminosity) coupled with *apparent* differences which are due to observer-dependent parameters (like orientation).”  

(B. Peterson, AGN, CUP 1997)

**TYPICAL PHYSICAL PROPERTIES:**

**Black Hole**

\[ m \sim 10^8 \, M_{\odot} \]

**Accretion disk (SS):**

\[ r \sim (10^{-2} - 10^{-3}) \, \text{pc} \]

\[ n \sim 10^{14} \, r^{-3/2} \, \text{cm}^{-3} \]

\[ kT \sim 30 \, \text{eV} \, r^{-3/4} \]

\[ v \sim 0.4 \, c \text{ (at inner edge)} \]

**Broad line region (BLR):**

\[ r \sim 0.01-0.1 \, \text{pc} \]

\[ n \sim 10^{10} \, \text{cm}^{-3} \text{ (forbidden lines collisional suppressed)} \]

\[ v \sim (10^3-10^4) \, \text{km/s} \]

\[ T \sim 10^4 \, \text{K} \]

**Torus:**

\[ r \sim 1 \text{ up to several } 10 \, \text{pc} \]

\[ n \sim 10^3 - 10^6 \, \text{cm}^{-3} \]

\[ T \sim \text{cold} \]

**Narrow Line region (NLR):**

\[ r \sim 100-1000 \, \text{pc} \]

\[ n \sim 10^3-10^5 \, \text{cm}^{-3} \]

\[ v \sim \text{a few } 100 \, \text{km/s} \]

\[ T \sim 10^4 \, \text{K} \]
If emitting region moves relativistically, observed features appear boosted:

Doppler factor: \[ D = \frac{1}{\Gamma_b (1 - \beta_b \cos \theta)} \]

- spectral flux enhancement: \[ S(\nu) = D^3 \, S'(\nu') \]
- energy/frequency shift: \[ \nu = D \, \nu' \]
- time variability: \[ \Delta t = \Delta t' / D \]
- ...

may expect to see some radio galaxies at HE with FERMI, but not much in TeV, if emission is (misaligned) BL Lac-type (SSC)
Fermi-LAT & VHE detection of misaligned radio galaxies

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Distance</th>
<th>HE detection</th>
<th>VHE</th>
<th>Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cen A</td>
<td>FR 1</td>
<td>3.7 Mpc</td>
<td>EGRET, LAT 2010</td>
<td>✔</td>
<td>No VHE variability</td>
</tr>
<tr>
<td>M87</td>
<td>FR 1</td>
<td>16 Mpc</td>
<td>LAT 2009</td>
<td>✔</td>
<td>1d- TeV variability</td>
</tr>
<tr>
<td>Fornax A</td>
<td>FR 1</td>
<td>18 Mpc</td>
<td>LAT 2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cen B</td>
<td>FR 1</td>
<td>56 Mpc</td>
<td>LAT 2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 1275</td>
<td>FR 1</td>
<td>75 Mpc</td>
<td>LAT 2009</td>
<td>✔</td>
<td>Month-type VHE**</td>
</tr>
<tr>
<td>IC 310</td>
<td>head-tail/BL Lac core?</td>
<td>80 Mpc</td>
<td>LAT 2010</td>
<td>✔</td>
<td>Day-type VHE</td>
</tr>
<tr>
<td>NGC 6251</td>
<td>FR 1</td>
<td>106 Mpc</td>
<td>EGRET, LAT 2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C 78</td>
<td>FR 1</td>
<td>124 Mpc</td>
<td>LAT 2010*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C 120</td>
<td>FR 1</td>
<td>142 Mpc</td>
<td>LAT 2010*</td>
<td></td>
<td>BLRG</td>
</tr>
<tr>
<td>3C 111</td>
<td>FR 2</td>
<td>213 Mpc</td>
<td>EGRET, LAT 2010*</td>
<td></td>
<td>BLRG</td>
</tr>
<tr>
<td>PKS 0943-76</td>
<td>FR 2</td>
<td>1360 Mpc</td>
<td>LAT 2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>......</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

out of ≥ 886 AGN ("Clean" sample): ≤ few %

* only in 1st LAT AGN catalog (missing in 2LAC/2FGL)

** day-scale HE (2yr LAT), Brown & Adams’11; very steep VHE spectrum (photon index 4), no signal above 600 GeV

Nolan+ (Fermi-LAT) ’12; Ackermann+ (Fermi-LAT) ’11; Abdo+ (Fermi-LAT) ’10
**Centaurus A**  \( (d \approx 3.7 \text{ Mpc}) \)

**Source Properties**
- BH mass \( \approx (0.5-1) \times 10^8 \text{ M}_{\odot} \)
- \( L_{\text{bol}} < 10^{43} \text{ erg/s} \ll L_{\text{Edd}} \)  (quasar SED)
- radio jet velocity \( \sim 0.5c \)
- jet inclination (VLBI) > 50°, modest beaming!
- complex radio morphology (jets, lobes etc)
- hybrid disk configuration (no bbb)

**TeV γ-rays from the core**
- 2004-2008 (>100h observation), 5σ detection
- VHE from 300 GeV - 5 TeV
- hard spectrum \( (\Gamma \approx -2.7 \pm 0.5) \)
- isotropic \( L(>250 \text{ GeV}) = 2.6 \times 10^{39} \text{ erg/s} \)
- no significant variability detected (low flux)
Recap III - VHE

Origin of VHE $\gamma$-rays from core of Cen A?

Radio galaxies @ VHE

Centaurus A ($d \approx 3.7$ Mpc)

A promising VHE candidate source:

Pointlike sources only $\gtrsim 1$ kpc apart. We therefore propose to perform a deep observation in 2006 (50 hrs livetime), spread over all the visibility window to maximize the chance to catch flaring states (e.g. by the nucleus/pc jet or microquasars/microblazars). With only one observing target, Centaurus A gives the unique opportunity to resolve, study, survey and monitor all these sources and components at the same time. Even in case of non detection, very meaningful upper limits will be obtained.

H.E.S.S. proposal by Felix+ 2005
Cen A @ High Energies - CORE

**Fermi: HE from the core (few kpc) of Cen A**
- detected at 4σ up to 10 GeV (10 months data)
- step spectra (photon index -2.7)
- isotropic $L(>100 \text{ MeV}) = 4 \times 10^{40} \text{ erg/s}$
- light curve consistent with no variability (15d bins)

**Modeling (misaligned BL Lac)**
- radio-GeV can be fitted with one-zone BL Lac type SSC assuming small Doppler factor ($D=1.2$) viz. large inclination angle (Chiaberge+ 2001)
- under-predicts TeV (even ignoring $\gamma\gamma$-absorption)
- emergence of additional component at VHE? R‘09, R‘11
Cen A @ High Energies - LOBES

HE from Giant “Radio” Lobes

- detected $>10\sigma$ up to $\sim6$ GeV (3 yr data)
- photon index $-2.6$, harder (trend) for Northern
- substantial extension of HE emission beyond radio/WMAP for Northern part
- HE gives model-independent info about spatial distribution of electrons

- Homogenous/single zone modeling not sufficient

Radio-synchrotron and HE-IC on CMB and EBL for injection $t=8\times10^7$ yr and $B\sim1\mu$G, $\gamma_{max}\sim10^6$, $<L_i>=E_{nth}/t;\sim10^{42}$ erg/s pp with $E_{pmax}=55$ GeV
**Source Properties**

\[ M_{\text{BH}} \sim (2-6) \times 10^9 \, M_{\text{sun}} \]

\[ L_{\text{bol}} \sim 10^{42} \, \text{erg/s} \ll L_{\text{Edd}} \]

\[ L_{\text{jet}} \sim 5 \times (10^{42}-10^{44}) \, \text{erg/s} \]

one-sided, kpc-scale jet  
jet inclination \( i \sim (15-25^\circ) \)  
modest Doppler (\( D \sim 2 \))

---

**2005 VHE high state:**

VHE spectrum **beyond 10 TeV**  
hard spectrum (\( \Gamma \approx -2.2 \)), hardening?  
isotropic \( L(>730 \, \text{GeV}) \approx 5 \times 10^{40} \, \text{erg/s} \)  
**rapid variability** (timescale 1-2 day)

**M87** (d\( \sim \)16 Mpc)
2008-February VHE flare:
mas radio (43 GHz) nucleus progressively brightened, suggestive of energetic particle injection close to BH
Day-scale activity implies compact zone

cf. IACT resolution ~ 0.1° = 30 kpc

Acciari+ 09, Science 325
2010-April VHE flare: well-defined rise and decline

\[ \Phi_{\text{VHE}}(t) = \Phi_0 e^{-|t-t_0|/\Delta t_{1/2}} \]

- H.E.S.S.
- MAGIC
- VERITAS

Abramowski+ 12
Detected up to 30 GeV in 10 months Fermi data (2008/09)
- Power-law photon index comparable to VHE (-2.2)
- isotropic $L(>100 \text{ MeV}) \approx 5 \times 10^{41}$ erg/s
- Detected light curve (10d bins) consistent with *no variability*
### Origin of variable VHE from M87 - possible interpretations

<table>
<thead>
<tr>
<th><strong>inner jet (sub-parsec)</strong></th>
<th><strong>leptonic</strong></th>
<th>decelerating flow (e.g. Georganopoulos+05)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>spine-shear  (e.g. Tavecchio+08)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mini/multi-blobs (e.g. Lenain+08)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>reconnection (e.g. Giannios+10)</td>
<td></td>
</tr>
<tr>
<td><strong>hadronic</strong></td>
<td>proton synchrotron &amp; p-γ (e.g. Reimer+04)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>jet-star interactions / pp (e.g. Barkov+12)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>combined lepto-hadronic (e.g. Reynoso+11)</td>
<td></td>
</tr>
</tbody>
</table>

**HST-1**
EC starlight photons (e.g. Stawarz+06)

**Magneto-sphere**
rotational acceleration & IC (e.g. R & Aharonian+08)

gap-type $e^+e^-$ acceleration & IC (e.g. Levinson & R 11)

---

**See R & Aharonian 2012 for details**
Heuristic arguments:

- Fermi extrapolation cannot explain high TeV flux (but perhaps normalization errors + variability)
- One-zone SSC (radio-GeV) cannot fit TeV high state (also other “conventional” misaligned models)
- Radio-TeV (‘08) link suggests close BH origin
- Day-variability implies compact zone
Example - Gap-type **particle acceleration** in M87
(e.g., Levinson’00; Neronov & Aharonian’07; Levinson & R. ’11; R. ’11)

- similar to pulsars
- rotating $\mathbf{B}$ induces $\mathbf{E} = -(\mathbf{\Omega} \times \mathbf{r}) \times \mathbf{B}/c$
- $\mathbf{E}$ supported by local charge density $\rho_{GJ} = \nabla \cdot \mathbf{E}/4\pi$ (Poisson)
- if $\rho < \rho_{GJ}$, unscreened $E_\parallel$ components $\Rightarrow$ particle acceleration
- **max. potential drop** $\sim 3 \times 10^{19} a M_9 B_3 (h/r_g)^2$ Volts
  - electrons $\gamma_e \sim 10^9 - 10^{10}$ possible (given curvature+IC)
  - proton energy $< 5 \times 10^{19}$ eV due to curvature losses or max. potential drop

Potential drawback:
- AGN environs tend to be plasma-rich - enough electric charges/field screening?
  - pair production in hot ADAF: $n_e/n_{GJ} = 10^{13}$ (accretion rate)$^{3.5}$ (Levinson & R ‘11)
How to produce **VHE gamma-rays** in M87: (Levinson & R. ’11)

- RIAF/ADAF soft photon field
- primary electron injection via *pair-production in hot RIAF/ADAF*
- *gap-type acceleration* of primary electrons up to $\gamma_e \sim 10^{10}$
- *direct IC* (KN regime) contribution (attenuated above 10 TeV)
- direct curvature contribution below 1 TeV
- *elm cascade* (initiated by absorption in ambient soft photon field)
- can have high enough *multiplicity* to ensure *force-free outflow*
RIAF/ADAF disk with $\alpha$ Bondi rate

- consistent with nuclear SED
- Calculate IR target field due to Compton scattering of synchrotron photon:
  - once or twice scattered: $L_c \propto L_s \times \{A \tau, A^2 \tau^2\}$ with $\tau \sim n_e \sigma_T r << 1$
  - $\tau_{\gamma\gamma} \propto L_c \propto (\text{accretion rate})^{2-4} \sim 0.2 - 5$ for $\alpha$ Bondi
- escape of $\leq 10$ TeV photons possible for gap models
- optical depth highly sensitive on accretion rate!

Can TeV gamma-rays escape unabsorbed?

(Levinson & R’11, R & Aharonian’12, cf. also Li+ 09)
Current caveats:

- Weak TeV source @ current IACT sensitivity limit (variability, extension)
- Want better constraints on GeV spectrum (extension? 50-100 GeV?)
- Need better statistics for temporal comparison (correlation?) and short-term analysis (minimum GeV variability timescale?)
M87 - Prospects for the future

_Astrophysical potential_

- disentangling origin of VHE emission & relevance of different models
- possible relation between TeV emission and jet formation
- proximity allows unique probe of EBL in transition region from mid- to far infrared ($\lambda \sim 30 [\varepsilon_\gamma /30 \text{ TeV}] \mu\text{m}$)

Centaurus A are shown in Fig. 11.5. The curves calculated for 3 different CIB models show that while Mkn 501 is best suited for the study of the CIB at wavelengths shorter than 20\(\mu\text{m}\), the two nearby radiogalaxies M 87 and Centaurus A can be very helpful providing us with $\geq 20$ TeV $\gamma$-rays for extraction of information about the CIB in the transition region from MIR to FIR, between 10 and 100\(\mu\text{m}\).
Cen A as possible UHECR accelerator?

Giant radio lobes

Scale ~ 50 kpc

Scale ~ 5 kpc

Complex morphology
Anisotropy in arrival directions & directional correlation with AGNs?

12th AGN Catalog by Veron-Cetty and Veron

Parameters:
- redshift $z < 0.018$
- threshold $E > 56$ EeV
- angular distance $\Delta \theta < 3.1^\circ$


cf. Kampert+ '12, ICRC

Correlation strength has decreased with time from $(62\pm10)\%$ to $(33\pm5)\%$, with currently (June’11) 28 out of 84 events correlating, with isotropic expectation $p_{iso} = 21\%$.

In current TA data (same AGN catalog & CR event selection), 11 out of 25 events (44%) correlate with AGN, with $p_{iso}=0.24$

(Telescope Array Collab.’12., arXiv:1205.5984)
Largest over-density of ECR is currently found in the region around Cen A (d=3.8 Mpc)

Largest departure from isotropy at $24^\circ$, with 19 CR events observed and 7.6 expected for isotropy
Efficient UHECR acceleration in Cen A?

(1) Direct electric field/unipolar inductor
   - BH magnetospheres in AGN...

(2) Diffusive shocks (Fermi I) acceleration
   - pc/kpc jet...

(3) Stochastic (Fermi II and shear) acceleration
   - kpc jet/lobes ...

cf. Martin Lemoine’s talk
does not look promising for protons
Assume rotating BH with angular momentum $J_{BH} = a GM_{BH}^2/c$ embedded in magnetic field

- $B$ rotates with angular velocity of horizon  
  *(membrane paradigm)*
- induced electric field $E \sim a B$
- available potential $\Phi \sim r_g E$

Maximum achievable cosmic ray energy:

$$E_{max} = Z e \Phi \sim 5 \times 10^{19} Z a M_{BH,8} B_4 (h/r_g)^2 \text{ eV}$$

**BUT:**

- **curvature losses** limit maximum energies *(Levinson’00; R’12)*

$$E_{max} \sim 8 \times 10^{18} B_{0,4}^{1/4} M_{BH,8}^{1/2} (r_c/r_g)^{1/2} (m_0/m_p) Z^{-1/4} \text{ eV}$$

- field screening expected: $h < r_g$, low BH mass & spin

---

see Rieger’11, IJMPD 20, for review
Maximum by equating $t_{\text{acc}}$ (shock) with escape timescale (cross-field) gives (ignoring radiative losses)

$$E_{\text{max}} \sim Z e B r_w \beta_s = (0.5-2) \times 10^{19} Z B_{0.4} \beta_{s,0.1} \text{ eV}$$

using $B(r) \sim 4 B_0(r_s/r)$, $B_0 \sim 10^4$ G and $\beta_s \sim 0.1$ c

But unlikely to work for protons as

- expect only mildly relativistic shock speeds $\beta_s \sim 0.1$
- would need jet power $> \text{FR I jet power}$
- nuclear SED compatible with low $D \sim \Gamma \sim 1$
Efficient 2nd order Fermi in outer lobes? - unlikely?

- acceleration timescale:
  \[ t_{\text{acc}} \sim \frac{E}{(dE/dt)} \sim \left( \frac{E}{dE} \right) t_s \sim \left( \frac{c}{v_A} \right)^2 \frac{\lambda}{c} \]

- Maximum when acceleration = escape (cross-field) ~ \( R^2/\lambda c \):
  \[ E_{\text{max}} \sim 2 \times 10^{19} Z (v_A/0.1c) (R/100 \text{ kpc}) (B/10^{-6} \text{G}) \text{ eV} \]

may account for PAO events if (!) \( v_A > 0.3 c \) (Hardcastle+ 09)

But: (1) Evidence for thermal soft X-ray emission suggests 
(Isobe+ 01; Marshall & Clark ‘81)
  ➞ thermal plasma density of \( n_{\text{th}} \sim (10^{-5} - 10^{-4}) \text{ cm}^{-3} \)
  ➞ Alfven speed \( \sim c/300 \ll c \) (cf. also O’Sullivan+ 09)

(2) Faraday RMs suggest densities \( \sim n_{\text{th}} \) (Feain+ 09)
Shear acceleration:

- Shear flow with frozen-in scattering centers:

\[ \vec{u} = u_z(x) \, \vec{e}_z \]

- like 2nd Fermi, stochastic process with average energy gain:

\[
\frac{\langle \Delta \epsilon \rangle}{\epsilon_1} \propto \left( \frac{u}{c} \right)^2 = \left( \frac{\partial u_z}{\partial x} \right)^2 \lambda^2
\]

with characteristic effective velocity:

\[ u = \left( \frac{\partial u_z}{\partial x} \right) \lambda \]

“2nd order Fermi-type”

(Jokipii & Morfill ’90; R. & Duffy ’04, ’06)
UHE protons via shear along kpc-jet in Cen A - perhaps possible

- **Advantage:** "distributed" mechanism operating along jet
- **"Disadvantage":** needs high energy seeds $t_{\text{acc}} \propto [(\partial u/\partial r)^2 \lambda]^{-1}$:
  
  $$t_{\text{acc, shear}} < t_{\text{adv}} \quad \text{possible for } \gamma_p \sim 5 \times 10^9 \quad (\text{using } \Delta r \sim r_j/2, \Delta v_z \sim 0.5c)$$

  \[ \Rightarrow \text{but:} \quad \text{could be provided by shock acceleration in inner part} \]

- **Energy boost** by factor $\sim(10-20)$ possible
  
  \[ \Rightarrow \text{constraint by confinement } r_{\text{gyro}} < \Delta r \]

  \[ \Rightarrow \text{may be more, if } B \text{ is amplified by shear} \quad (\text{Urpin'06; Zhang+ '09}) \]

- **Spectral change** possible due to operation of new mechanisms!
Astrophysical significance of variable VHE from M87

Fundamental diagnostics of
- acceleration & radiation mechanisms
- near-black-hole environment
- link between TeV emission and jet formation
- EBL studies ...

Cen A as possible UHECR source

- observationally “motivated”, theoretically “possible”:
  - protonic - unlikely, perhaps via shear along kpc jet
  - heavier - possibly also via BZ and shocks
  ➔ spectral changes might be partly due to operation of different mechanisms
  ➔ not all are linearly rigidity-limited
THANK YOU!

For more details see recent review papers:
(1) Non-thermal Processes in Black-Hole-Jet Magnetospheres, IJMPD 20 (2011), 1547-1596
(2) Probing the central black hole in M87 with gamma-rays (with Felix), Mod. Phys. Lett. A 27 (2012)