Pinpointing the Gamma-Ray Emission Region in M87 using TeV and 43-GHz Radio Monitoring

R. M. Wagner
Max-Planck-Institut für Physik, München
and Excellence Cluster “Origin and Structure of the Universe”, Garching

on behalf of the VERITAS, MAGIC, and H.E.S.S. Collaborations and the M87 43-GHz Monitoring Team
Close-by radio galaxy: 
~16.7 Mpc (z=0.00436)

Radio structure: 
outflows and halo

Jet angle: ~30° ➞ not a blazar! 
But inner region < 19°

Central black hole: 
$M_{BH} \sim 6 \cdot 10^9 \text{ M}_\odot$ Gebhardt+Thomas09

Highly structured jet, 
knots resolved in radio, optical 
and X-rays

Jet is variable: flares in radio, 
optical and X-rays

Unique laboratory to study blazar 
and jet physics
X-ray/optical/radio knots: concentrated structures... shocks?

Radio/optical: similar polarization synchrotron emission

X-ray: spectrum with $\alpha = 2.0-2.9$ synchrotron emission?

Inner jet: superluminal motion (~2c) => relativistic particle population

Variability time-scales: weeks to months to years

Predictions of VHE $\gamma$-ray and UHECR particle emission
The Relativistic Plasma Jet of M87

Variability time-scales:
weeks to months to years

Predictions of VHE $\gamma$-ray and UHECR particle emission

Harris+09

Wilson&Young02

Radio (VLA)

Optical (HST)

X-ray (Chandra)
M87: 10 Years of VHE Observations

- >4σ excess seen by HEGRA in 1999
- 11σ detection by H.E.S.S. 2003/4,
- Signal confirmed by MAGIC and VERITAS 2005-8
- Day-scale flares 2005 H.E.S.S., 2008 MAGIC
- Variations on timescales of years
- Energy spectrum stable
  - hard: $\alpha = -2.3$
  - 100 GeV to 20 TeV
The 2008 Joint VHE Campaign

- Coordinated observations: VERITAS/MAGIC/H.E.S.S.
- plus 5 Chandra pointings in 2008
- Coverage: 120h, 50 nights
- Outburst in February 2008 (2 weeks after a MAGIC trigger, X-ray low-state of HST-1)
- Confirmed short-term variability

X-ray (Chandra)

**HST-1:** unlikely source of VHE emission
VLBA Monitoring of the M87 jet at 43 GHz (2007/8), Walker et al.

- Resolution: 0.43x0.21 mas
- 100 Schwarzschild radii
  - = 0.37 mas (1 mas = 0.078 pc)

Jet formation @ 30 x 60 Rs

VHE flare accompanied by radio flare from BH vicinity
VHE/Radio Collaboration Reveals...

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2nd Fermi Symposium, Washington (DC), November 4, 2009
Time-dependent electron injection into slow outer sheath ~VHE flux
First non-blazar emitting VHE $\gamma$-rays: Misaligned blazar, AGN unification?

Short-term variability:
- Excludes models
- Constrains size of emitting region ($R \leq 5 \times 10^{15}\delta$ cm, $\sim 100$ $R_{schw}$)

Hard energy spectra:
- Modeling, emission mechanism

Upper limit on VHE extension:
- 14 kpc $\rightarrow$ location unknown

Radio/TeV connection:
- First experimental evidence: charged particles accelerated in BH vicinity

**Key question:** origin/(location) of the TeV emission
M87 (non-simultaneous) SED

Data non-simultaneous
Partly published before TeV flaring was known in M87

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M87: Importance of Results & Future

**TeV/radio connection:**
- TeV emission from BH vicinity
- Important input for TeV modeling
- Accretion & jet formation physics

**Future questions:**
- Can pattern be observed repeatedly?
- TeV emission & radio core: How close to BH?
- More detailed sampling of light curves
- Other TeV sources: Similar pattern?

**Fast variability!**
- Magnetic Field in the Jet
  - BH
  - Shock: knots
  - Deceler: \( \Gamma = 20 \), \( \Gamma' = 5 \)

**Fast variability!**
- Magnetic Field in the Jet
  - BH
  - \( \Gamma \geq 50 \)
  - 1 zone

**Fast variability!**
- Spine-Sheath Configuration
  - BH
  - \( \Gamma = 10 \)
  - \( \Gamma \geq 50 \)
  - 2 zone

**Velocity Gradient along Jet**
- Multi-Blob SSC model
  - BH
  - \( \Gamma \leq 10 \)
  - Blobs

**BH Magnetosphere**
- BH MHD