Recent Progress in the Study of High Energy Emission from AGN jets

活動銀河核からの高エネルギー放射:最近の進展

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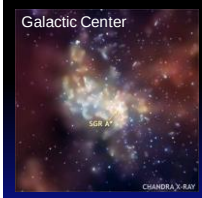
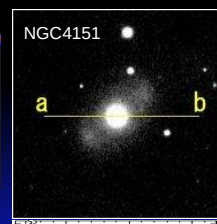
On behalf of the Fermi/LAT collaboration

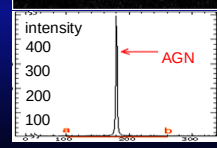
Outline

- Introduction to AGN jet
- Large scale jets & lobes in Radio Galaxy
- Blazars in Fermi-era
- Mis-aligned AGN with Fermi-LAT
- Towards AGN unification

AGN = Super Massive BH







- Each galaxy hosts SMBH (M_{BH} ~$10^{6\text{-}10}M_s$) in its center and each SMBH accretes at some levels from surrounding interstellar medium.
- AGN accretes at **"high rate".**
  - Extremely bright: ~ 100-1000 L_{Gal}
    → $L_{rad} < L_{edd} \sim 10^{38}(M_{BH}/M_s)$ [erg/s]
  - Fast time variability: ~ 10^3-10^6 s
    → $t_{var} > R/c > R_g/c \sim GM_{BH}/c^3$

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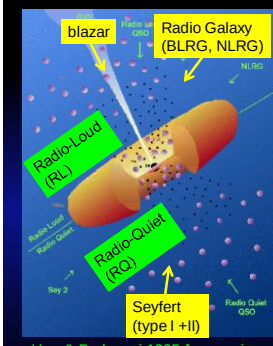
Zoo of AGN; Unified Scheme

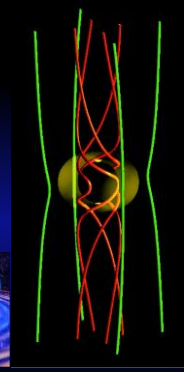


Urry & Padovani 1995 for a review

- Quasars ($\sim 10^{-7}$ Mpc^{-3})
  Radio-quiet or radio-loud quasars
- BL Lacertae Objects ($\sim 10^{-7}$ Mpc^{-3})
- Radio Galaxies ($\sim 10^{-6}$ Mpc^{-3})
  Broad or narrow line radio galaxies
  Fanaroff-Riley class I or II
  …any many more…
- Seyfert Galaxies ($\sim 10^{-4}$ Mpc^{-3})
  Seyferts type 1 - 2
  Narrow-Line Seyferts
- Low-Luminosity AGN ($>10^{-3}$ Mpc^{-3})
  Low-Ionization Nuclear Emission-Line Region Galaxies
  "Regular" spiral galaxies like our Galaxy (Sgr A*)…

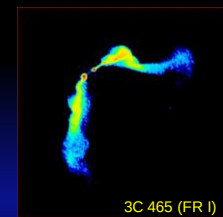
Relativistic Jets

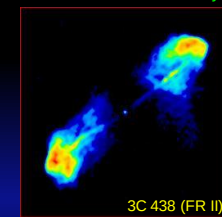
- Blandford-Znajek process is thought to be one of the best explanations to extract energy from rotating BH.
- With rotating BH embedded in an external B-field (supported by an accretion disk), electro-magnetic currents are driven and the energy is released in a form of magnetized jets.
- For maximally spinning BH;
  $E_{tot} \sim M_{BH}c^2 \sim 10^{63}(M_{BH}/10^9M_s)$ [erg]
  $P_{max} \sim cBR_g^2/4\pi \sim 10^{46}(M_{BH}/10^9M_s)$ [erg/s]
- Interestingly, $P_{jet} \sim P_{max}$ for most AGN jet sources, where P_{jet} is kinetic luminosity of jets.
- Jet content? – still unknown.



Radio Galaxy: FR I / FRII

FR = Fanaroff & Riley

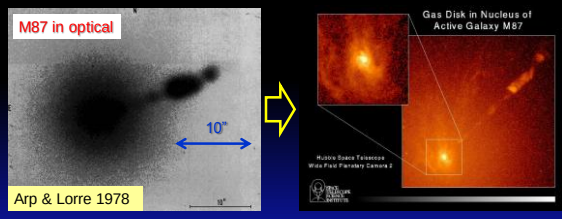




- Low power ($10^{42\text{-}44}$ erg/s)
- Low Γ
- Core brightened
- Bending (ram pressure)
- Decelerating (mass entrainment)

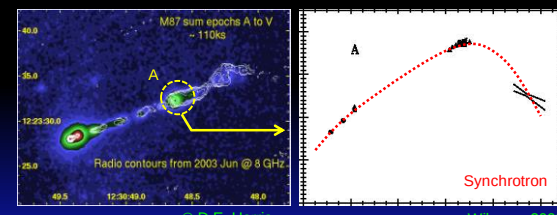
- High power ($10^{44\text{-}46}$ erg/s)
- High Γ
- Edge brightened
- Collimated, straight jet
- Deceleration negligible?

AGN Jet =Acceleration Site



- The jet-like feature in M87 was first reported in Curtis 1918 (!) .
- Electron synchrotron life times in equip fields t_{opt} ~ 100 yr, while the projected length of jet much larger: D ~ 1.5 kpc.
- This suggests *in situ* acceleration within "knots".
  - ✓ internal shock due to velocity irregularities in the beam (Rees. 1978)

FR-I: M87 w/ Chandra



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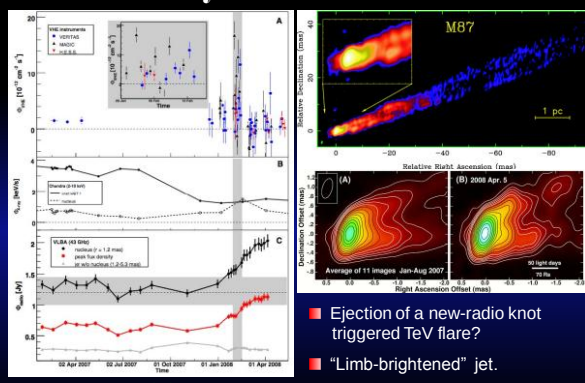
- Single SED can fit radio to X-ray: Electron sync model can work.
  → X-ray emitting electrons: E_e = 10~ 100 TeV for B_{eq} ~ 100μG.
- But, we should always keep in mind various assumptions;
  (1) "B ~ B_{eq}" to get various jet parameters.
  (2) emitting volume is "same" for all wavebands.
  (3) filling factor ~ 1 and uniformity… etc

Closest vicinity of SMBH

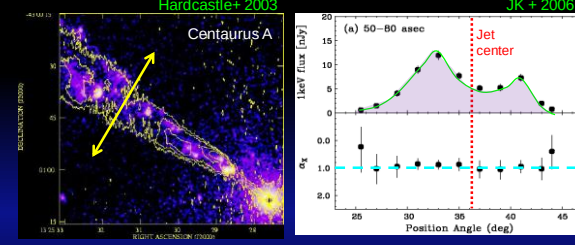


Wagner +2009, Acciari+ 2010

- Ejection of a new-radio knot triggered TeV flare?
- "Limb-brightened" jet.

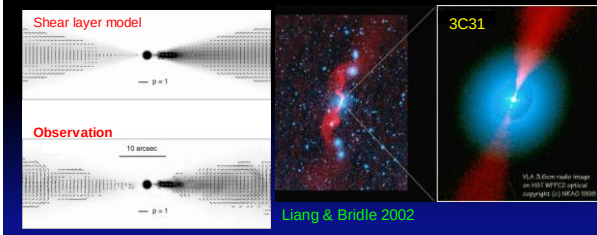
Inner Knot X-ray Emission ?

Hardcastle+ 2003 — JK + 2006



- Not only bright X-ray knots, but continuous, diffuse emission between knots . Log N-log S also confirms "diffuse" emission.
- For the nearest FR-I Cen-A, "double-horn" profile in trans. direction.
  - ✓ Stratified jet – fast spine & slow sheath ?
  - ✓ Turbulent acceleration (Fermi II) at work over the jet volume ?

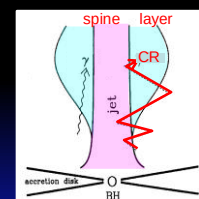
FRI: Velocity Shear

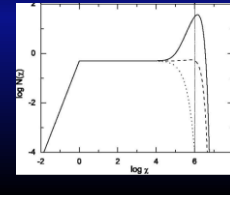


Liang & Bridle 2002

- Decelerated jet model with "shear layers" successfully explain observation of 3C 31 and 3C 315.
- "Velocity gradient" is naturally expected via the Jet-Matter. interaction.
  - ✓ K-H instability → mass entrainment.
  - ✓ Transfers momentum and energy to ambient medium.
  - ✓ Mixing layer, deceleration of jet …

Turbulent Acceleration





- Stratified jet – "spine" + "layer".
- Unlike Fermi-I, turbulent acceleration (Fermi II) can produce very hard electron distribution.
- If field is very turbulent (ξ~ 1), electrons "pile-up" as it never escape from the region.

$$t_{acc} \sim \frac{3\lambda_e}{c}\left[\frac{c}{V_A}\right]^2 \sim 5\times10^9\,\gamma_8\,B^{-1}_{100\mu}V^{-2}_{A,8}\ [s]$$

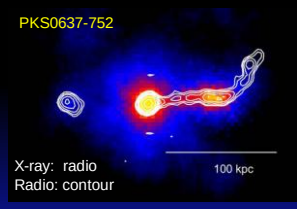
$$t_{esc} \sim 3\left[\frac{L}{V_A}\right]^2\frac{c}{\lambda_e} \sim 6\times10^{15}\,\gamma_8^{-1}B_{100\mu}L^2_{100pc}\ [s]$$

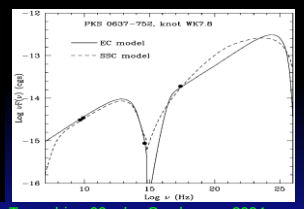
$$\Rightarrow t_{esc}/t_{cool} \sim 10^7\,(B_{100\mu G})^3(L_{100pc})^2\xi^{-1}$$

where $\xi = U_B/U_T$

Ostrowski 2000, Stawarz & Ostrowski 2002
Stawarz & Petrosian 2008

FR II/QSOs: bright X-ray jet



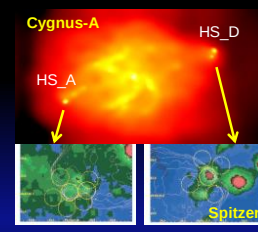


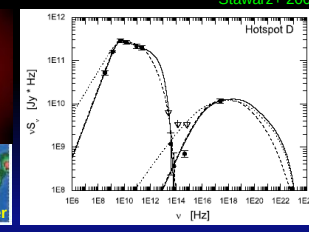
Tavecchio+ 00, also Sambruna+ 2004

- Ultra-luminous X-ray jets:
  - NOT smoothly connecting w/ radio-optical synchrotron.
  - IC/CMB is more likely if Γ_{jet} ~10 on Mpc scale ($\propto \Gamma_{jet}^2 U_{CMB}$).
- Consistent w/ VLBI observation (β_{app} ~ 13.3: Edwards+ 06)
- More and more samples: http://hea-www.harvard.edu/XJET/

FR II: Hotspots

Stawarz+ 2007

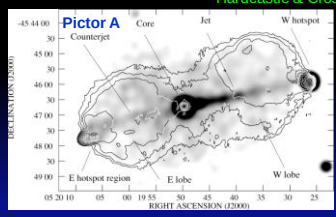


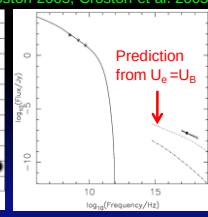


- X-ray emission of hot-spots in high-power FR II jet is consistent w/ synchrotron self-Compton (SSC) model close to $U_e \approx U_B$.
- The hot-spots in low-power jets is too bright in X-ray, suggesting instead synchrotron in origin (Hardcastle et al. 2004).
- Multiple structures often observed; relic? swing of jet-head?

FR II: X-rays from Lobe

Hardcastle & Croston 2005, Croston et al. 2005

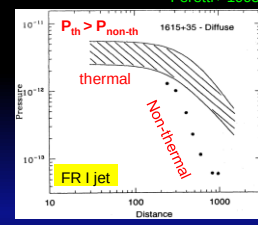




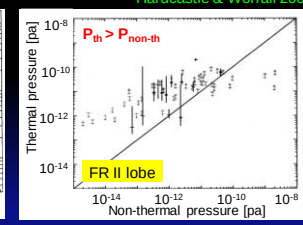
- X-ray emission is most likely due to IC/CMB under approximate equipartition between U_e and U_B ($0.3 < B_{IC}/B_{eq} < 1.3$)
- Several "warnings", however, due to (1) extrapolation of radio spectrum to lower energy, (2) unknown filling factor, (3) contamination of cluster gas (see discussion in Worrall et al. 2009)

Calorimetry & Jet Content

Feretti+ 1995



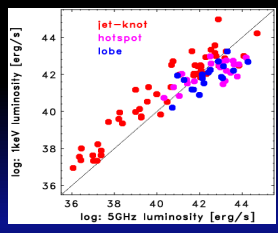
Hardcastle & Worrall 2000

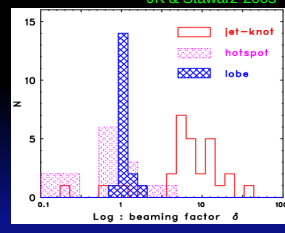


- It has often been suggested that min. pressure in FRI /FRII jets is normally below that of external X-ray emitting medium.
- Maybe significant contribution from protons and/or thermal electrons, but still premature (e.g., Croston+ 08).
- Independent approach from "cocoon-dynamics" also suggests invisible matter in FR II jets (e.g., Ito+ 08).

Systematic Study

JK & Stawarz 2005

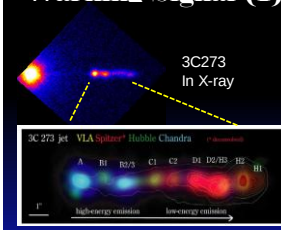


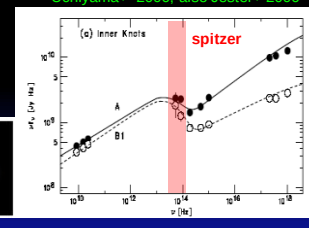


- Distribution of 44 AGNs (56 knots, 24 hotspots, 18 radio lobes).
- A very simple assumption: apparent deviation from equipartition is due to Doppler enhancement, i.e. beaming factor δ.
- Actually, extremely X-ray bright knots can be explained if δ ~ 10, which is consistent w/ PKS0637-752 (classified also as blazars.)

Warning Signal (I)

Uchiyama+ 2006, also Jester+ 2006

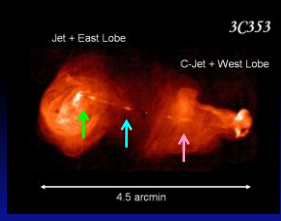


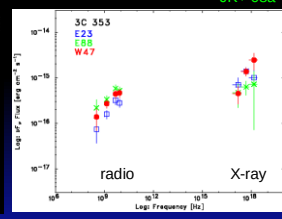


- IR imaging of the jet of 3C 273 by *SPITZER* clearly confirms that optical jet emission is dominated by the 2nd, high E component.
- Both the radio and optical components are linearly polarized to a similar degree of ~ 15% - "double" synchrotron???
- Smooth connection between X-ray and optical: same origin?

Warning Signal (II)

JK+ 08a

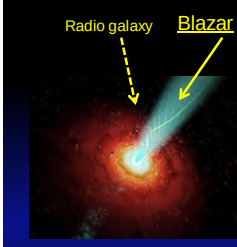


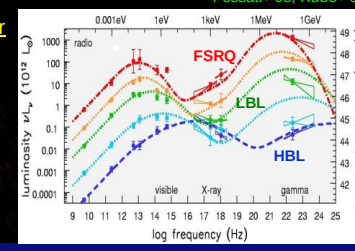


- The 4th strongest FRII radio galaxy in 3C catalog.
- First clear detection of "X-ray counter-jet" by Chandra.
  - ✓ If jet is highly relativistic, $\delta \approx 1/\Gamma_j$, hence Doppler "de-beamed".
- Again, "double Sync" or "Sync tail" more likely?
  - ✓ $E_e \sim 200\ (\Gamma_j/10)$ TeV ; presence of "ultra-rel." electrons.

Blazars

Fossati+ 98, Kubo+ 98



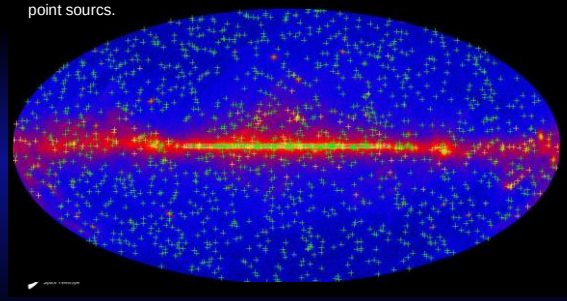


- Blazars: jet closely aligned to our line of sight.
  - SL motion, one-sided jet ➪ $\beta_{jet} \sim 0.99\ c$ or $\Gamma_{jet} \gtrsim 10$
- "Double peaks" over two decades in ν.
  - Sync + Inv. Compton, but wide variety ➪ HBL, LBL, FSRQ
  - Most powerful objects peaks at low ν ➪ "Blazar Sequence"

Now we have Fermi !

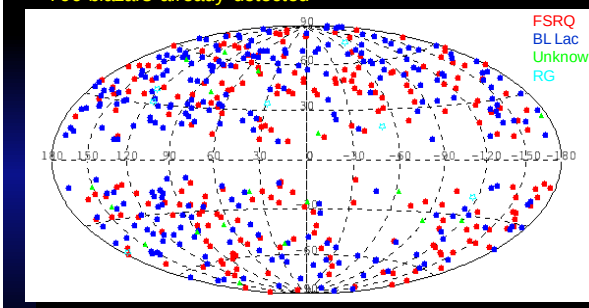
1451 sources in 1FGL catalog.
- about 60 % sources have "association".
- clear separation between diffuse and point sources.

Abdo et al. 2010a

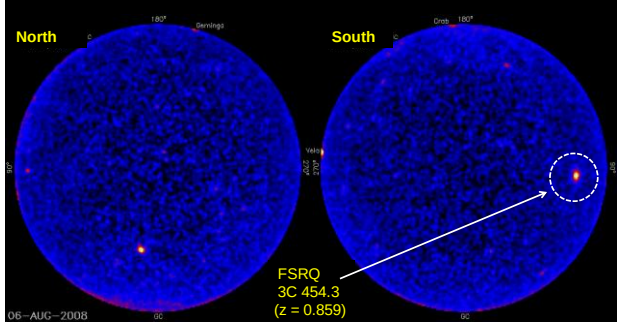


AGN map w/ Fermi-LAT

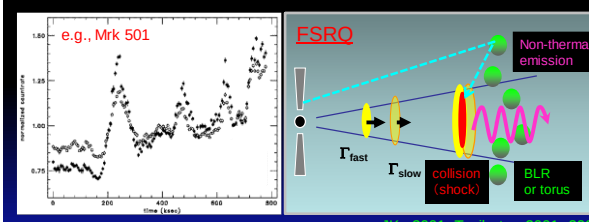
~ 700 blazars already detected



"Variable sky" everyday!



Internal shock in blazars

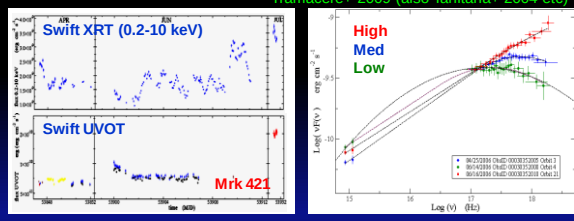


JK+ 2001, Tanihata+ 2001, 2003

- Rapid variability suggests: $R \sim c\ t_{var}\ \delta \sim 10^{-3}$ pc.
- Only little variability below t_{var} <<1d : "Internal shock"
  - Modulation of relativistic outflows : $D \sim 10\ \Gamma_{jet}^{\ 2}\ R_g \sim 0.01$ pc
    ➪ sub-pc jet (the first site of E-dissipation)
  - "Jet power" & "seed photons" control the blazar sequence.

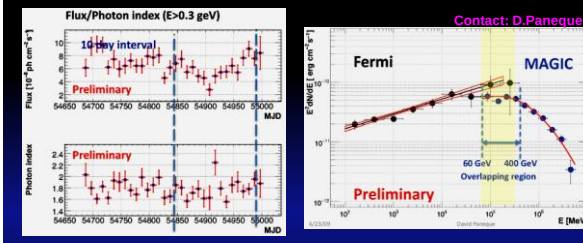
Spectral Evolution of HBL

Tramacere+ 2009 (also Tanitaha+ 2004 etc)



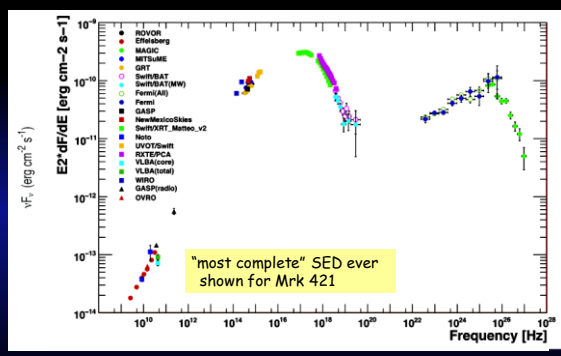
- Significant evolution *only* at X-rays, i.e., no significant variation at UV-optical: $E_p \sim 1$ keV $\rightarrow$ 10 keV.
- This has been argued as sudden increase of electron γ_{max} . (e.g., Takahashi + 1996, 2000, JK+ 1999, 2000)
- $\nu_{max} \propto \xi^{-1} \delta\, \nu_s^{\,2}$ (ξ: gyro factor, δ: beaming factor, v_s: shock speed)

Fermi Observation of Mrk 421



- Significant variability, but not as impressive as those in X-rays.
- Hard Gamma-ray spectrum with $\Gamma = 1.79 \pm 0.03$ – nicely overlap w/ the energy ranges covered by the ground Cherenkov telescopes.
- MAGIC data, simultaneously taken during a low state nicely connects w/ Fermi-LAT data - spectral break at ~ 100 GeV?

SED of Mrk 421 (average)

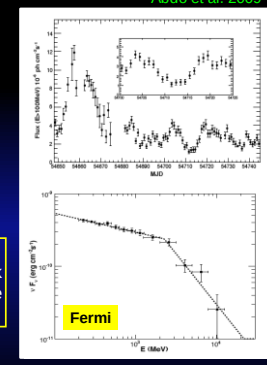


Fermi Observation of FSRQ

Abdo et al. 2009

- 3C454.3 at z = 0.859
  Detected by EGRET, AGILE.
  Very active since 2000.
- Fermi-LAT data show rapid, quasi-symmetric, flares on a time scale of ~3 days.
- First observation of a spectral break above 100MeV.

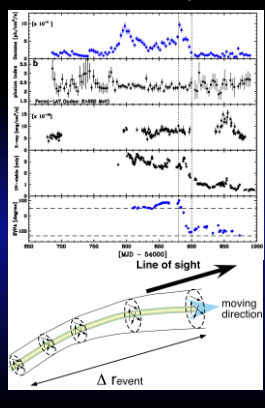
A possible interpretattion:
Direct signature of an intrinsic break in the energy distribution of the radiating particles?

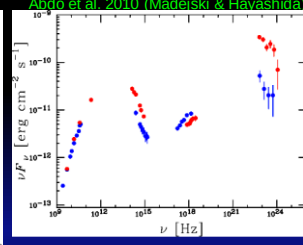


Contact Author: G.Madejski & B.Lott

Case of 3C 279

Abdo et al. 2010 (Madejski & Hayashida)



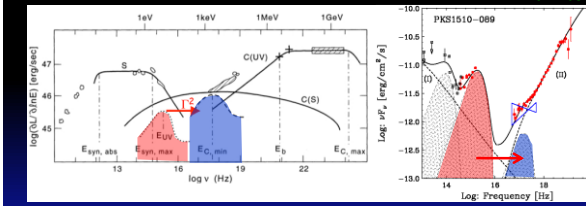


- Coincidence of γ-ray flare and change in opt. polarization (KANATA)
- Significant drop of Polarization.
- EVPA changes by 208°

Curved jet ???

Suzaku observation of FSRQ

JK+ 08b

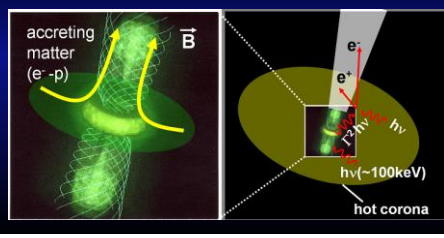


- "Seed" for the ERC process is UV photons reflected by the BLR. $E_{diff} \sim 10$ eV, $L_{diff} \sim 10^{46}$ erg/s
- Before the "blazar zone", fast /slow shells up-scatter UV via the "bulk-Comptonization" to $E_{BC} \sim \Gamma_{BLK}^{\,2} E_{diff} \sim 1$ keV.
- BC luminosity depends on the jet composition : $L_{BC} \propto (n_e/n_p)\, L_{jet}$

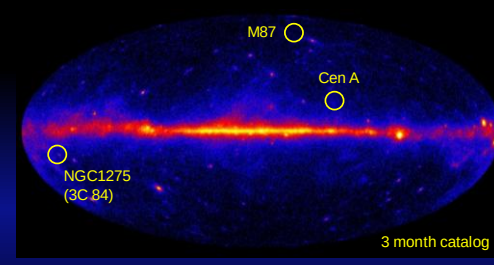
$\Rightarrow$ $\Gamma \sim 20$, $r \sim 1$pc, $n_e/n_p \sim 10$, B~ 0.6 G, $L_e/L_p \sim 0.05$

Jet Launching - speculation

- Jet is launched near a rapidly rotating black hole, presumably via Blandford-Znajek process.
- Such a jet, initially consisting of *e-p*, is accelerated by large scale B-field stresses, and within 100 R_g, it can be loaded by e^-e^+ pairs via interactions with the coronal soft γ-ray photons.
- Hence, it is possible that relativistic jets may well contain more e^-e^+ pairs than *p*, but are still dynamically dominated by cold *p*.

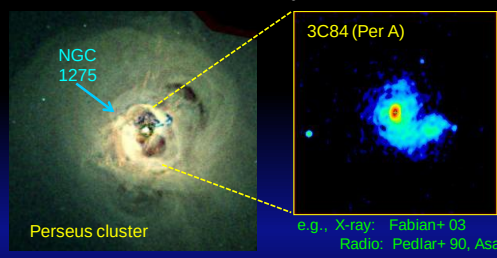


Non-blazar type AGN?



- 2 radio galaxies, NGC 1275 and Cen A have been detected in the first 3 month catalog (Abdo et al. 2009)
- Very recently, M 87 also detected at 10 σ level based on ten-months of all sky LAT data. (Abdo et al. 2010)

New Comer: NGC 1275 ?

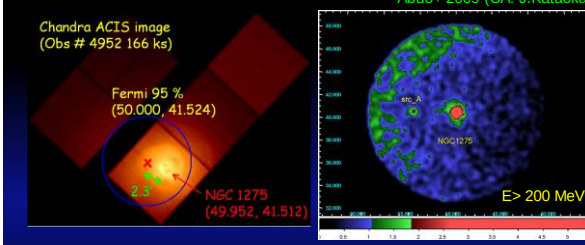


- Perseus cluster hosts the giant elliptical galaxy NGC 1275 at its center. Shocks and ripples are clearly evident in deep Chandra image.
- In radio, NGC 1275 hosts the exceptionally bright radio source Per A, also known as 3C 84.

AGN, or dark matter annihilation ?

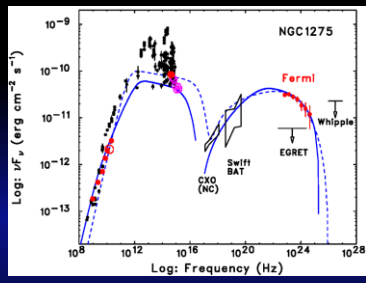
Fermi-LAT detection of NGC 1275

Abdo+ 2009 (CA: J.Kataoka)



- Clear excess at the position of Perseus/NGC 1275 complex .
- About an order of magnitude brighter than EGRET UL – significant brightening on decade time scale.
- The positional center of the γ-ray emission is only **2.3'** apart from the nucleus, 3C 84, well within the 95% LAT error circle.

SED of NGC 1275

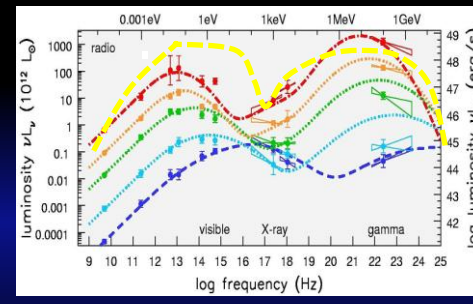


(1) one-zone SSC
B= 0.05 G
R= 0.7 pc
δ= 2.3, Γ = 1.8
L_{jet} = 2.3e45 erg/s

(2) Decelerating flow
B = 0.2 G
D = 0.2 pc
R = 0.01 pc
Γ = 10 -> 2
L_{jet} = 6.0e43 erg/s

- Possible unification of BL Lac and Radio Galaxies !
- Jet power close to the power required to inflate the lobes of 3C 84 against the pressure of the hot cluster gas. (0.3-1.2)x 10^{44} erg/s: Dunn & Fabian 2004

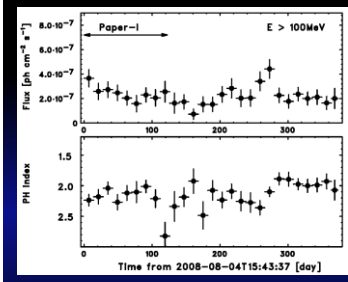
However... if NGC 1275 is "beamed"?



- Similar to LBLs, but much brighter ($L > 10^{48}$ erg/s).
- Dominated not by a jet "spine" ($\Gamma_j \sim 10$), but by the slower jet boundary layers? ($\Gamma_j \sim$ a few).

Long term variability

JK+ 2010

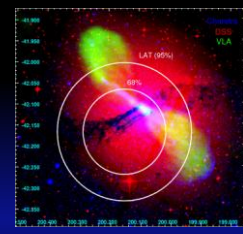


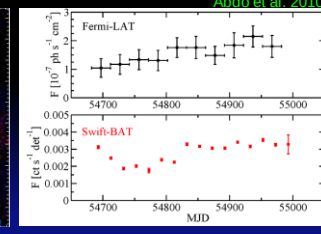
The highest energy photon was 67.4GeV with an angular separation of only 2.4 arcmin from the nucleus.

- Variability detection, as expected.
- Spectral cutoff at E_c = 41.2±18.8 GeV, perfectly consistent w/ VERITAS U.L. (Acciari+, 2009. astro-ph/0911.0740)

Core (nucleus) of Cen A (I)

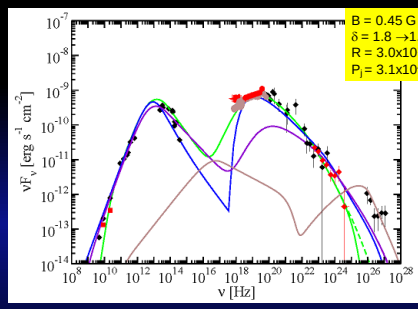
Abdo et al. 2010





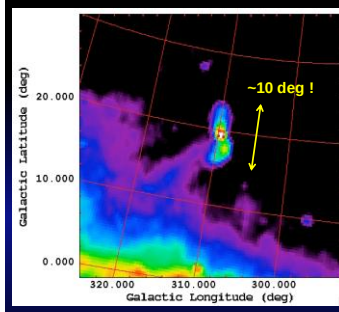
- Steep LAT spectrum of $\Gamma = 2.67 \pm 0.10$, with detectable variability (correlated with Swift-BAT).
- A single, one-zone SSC fit the MW data from radio to GeV, but fails to explain non-simultaneous HESS data.
- γ-rays may be originated from slower portion of the jet, i.e., sheath.

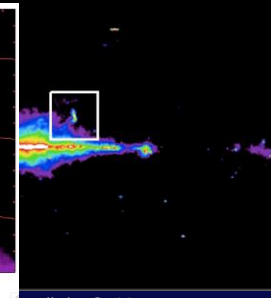
Core (nucleus) of Cen A (II)



The green curve is a synchrotron/SSC fit to the entire data set. The dashed green curve shows this model without γγ attenuation. The violet curve is a similar fit but is designed to under fit the X-ray data, and the brown curve is designed to fit the HESS data while not over-producing the other data in the SED. The blue curve is the decelerating jet model fit (Georganopoulos & Kazanas 2003).

Cen-A Lobe in Radio-band



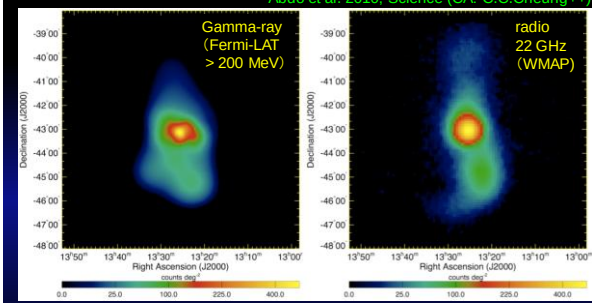


All sky @408 MHz (Haslam et al. 1982)

- Spatial extent of ~ 10 deg; A possible Cosmic-ray accelerator? (Hardcastle et al. 2009)

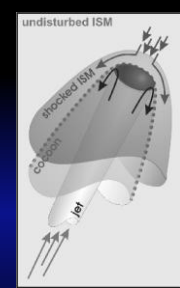
Fermi-LAT detection of Cen-A Lobe

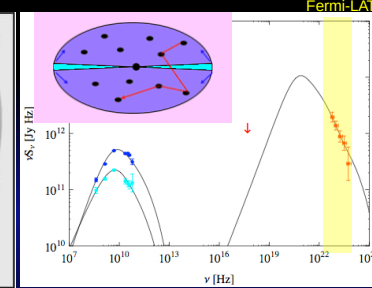
Abdo et al. 2010, Science (CA: C.C.Cheung++)



- South lobe immediately obvious; North lobe lower surface brightness.

Why Important? : (I) Acceleration

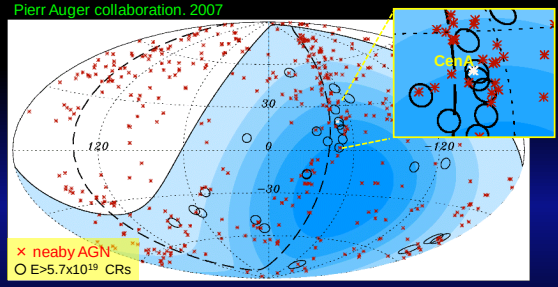




- Good IC (CMB+EBL) fits of LAT spectra with **B ~ 0.9 μG in both lobes.**
- U_e/U_B ~ 3.6 (north) and 1.3 (south), i.e., close to equipartition
- **t_{cool} < R/c for GeV emitting electrons: accel. over all the volume.**

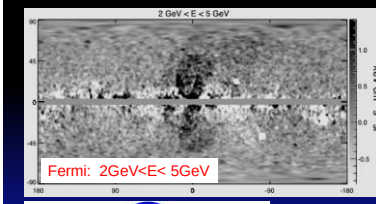
Why Important? (II) Relation to CR?

Pierr Auger collaboration. 2007

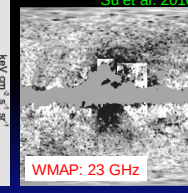


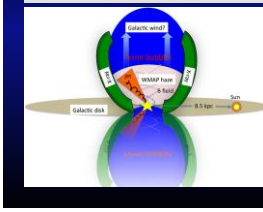
- Anisotropic distribution of $E > 5.7 \times 10^{19}$ eV Cosmic Rays.
- Correlation to neaby AGNs?→ Highest energy CRs may be accelerated in situ.

Galactic Haze (gamma-ray bubble)



Su et al. 2010



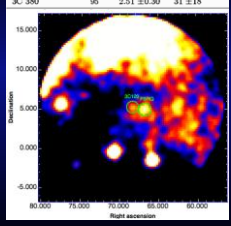


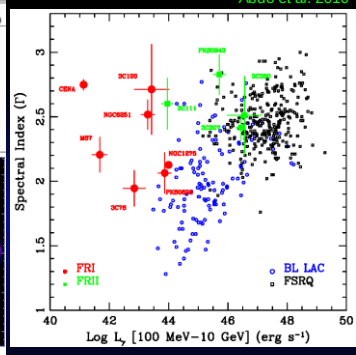
- Fermi-LAT reveals large γ-ray bubbles, extending 50° above/below Gal. plane.
- Correlated w/ WMAP haze, suggesting IC/CMB in origin.
- Similar to Radio Lobe in AGN - past activity of Sgr A* ?

More RGs detected!

Abdo et al. 2010

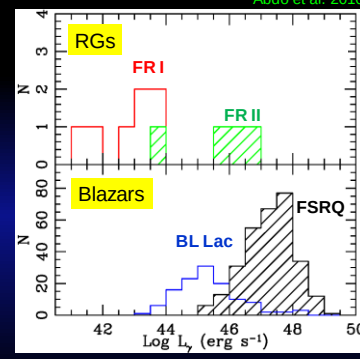
Object	TS	Γ	Flux[a] (> 100 MeV)
3C 78/NGC 1218	35	1.95±0.14	4.7 ±1.8
3C 84/NGC 1275	4802	2.13± 0.02	222 ±8
3C 111	34	2.54 ±0.19	40 ±8[c]
3C 120	32	2.71±0.35	29 ±17
PKS 0625-354[d]	97	2.06±0.16	4.8 ±1.1
3C 207	79	2.42 ±0.10	24 ±4
PKS 0943-76	65	2.83 ± 0.16	55 ±12
M87/3C 274	194	2.21 ± 0.14	24 ± 6
Cen A	1010	2.75± 0.04	214 ±12
NGC 6251	143	2.52 ±0.12	36 ±8
3C 380	95	2.51 ±0.30	31 ±18





RG vs Blazars

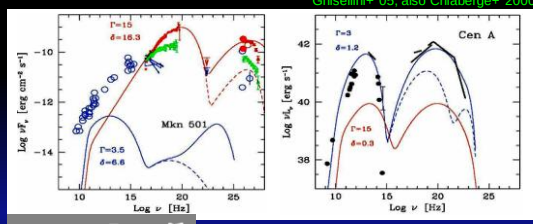
Abdo et al. 2010

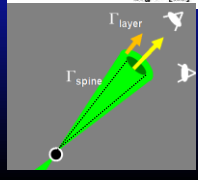


- The γ-ray luminosities of FRI radio galaxies are significantly smaller than those of BL Lac objects detected by the LAT.
- Whilst, the γ-ray luminosities of FRII sources are quite similar to those of FSRQs, which could reflect γ-ray emission dominated by slower sheath.

RGs as a Gamma-ray Emitter

Ghisellini+ 05, also Chiaberge+ 2000

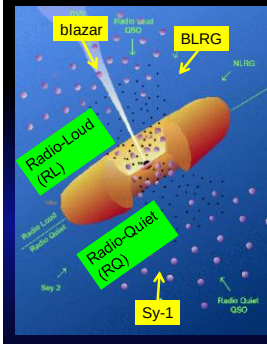


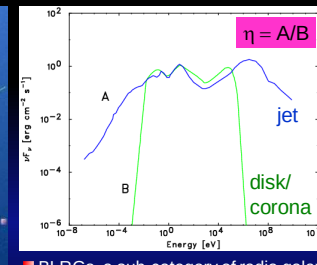


- RGs may/should be "mis-aligned" blazars
  - low power FR I ⟷ BL Lacs
  - high power FR II ⟷ FSRQs
- SED modeling on-going

Spine dominated ….. Blazars
Layer dominated ….. RGs

Towards AGN Unification

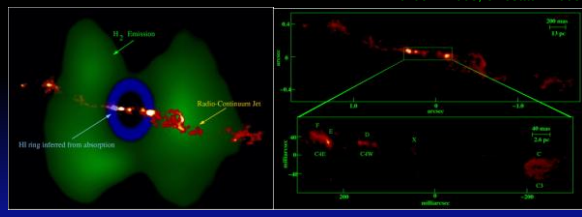




- BLRGs, a sub-category of radio galaxy, are ideal targets since we expect significant contribution from *both* (A) jet and (B) disk & conona.
- BLRG (radio loud) ↔ Sy-1 (radio quiet)

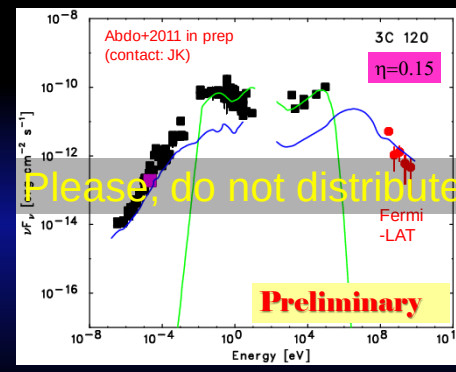
"Weak Jet" in Seyfert

Mundell+ 2003, Ulvestad+ 2005

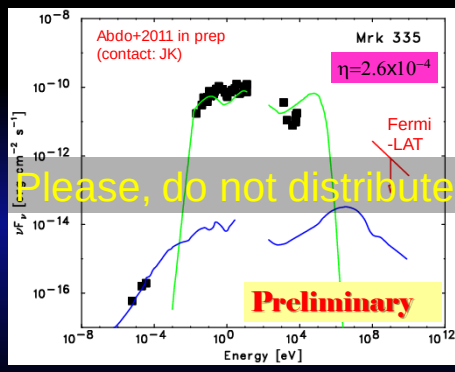


- 240-pc jet in NGC 4151 (Seyfert) is two-sided and highly collimated (diameter < 1.4 pc).
- Knotty morphology seems to be related to shocks formed as the jet interacts with small ISM clouds.
- $L_R \sim 10^{37}$ erg/s. No evidence for relativistic bulk velocities (knots' velocities < 0.03c at 0.1-10 pc scales).

Example Fitting of BLRG (RL)



Example Fitting of Sy-1 (RQ)



Summary

I have reviewed most recent observational highlights from AGN jets viewed at high energies.

- Recent survey of large-scale jets with CXO have brought us new insights on the kpc/Mpc scale jet - jet structures, turbulent acceleration, ultra relativistic electrons above 100 TeV.
- Unprecedented sensitivity of Fermi/Suzaku provides new challenges to the blazar physics - Unification of blazars and radio galaxies are being more common.
- Further challenge to "AGN unification (RL&RQ)" on going.

More will come soon w/ Fermi-LAT!