A Role of Galactic Dust and Starlight in Shaping the γ-ray Emission of FR I and BL Lac Sources

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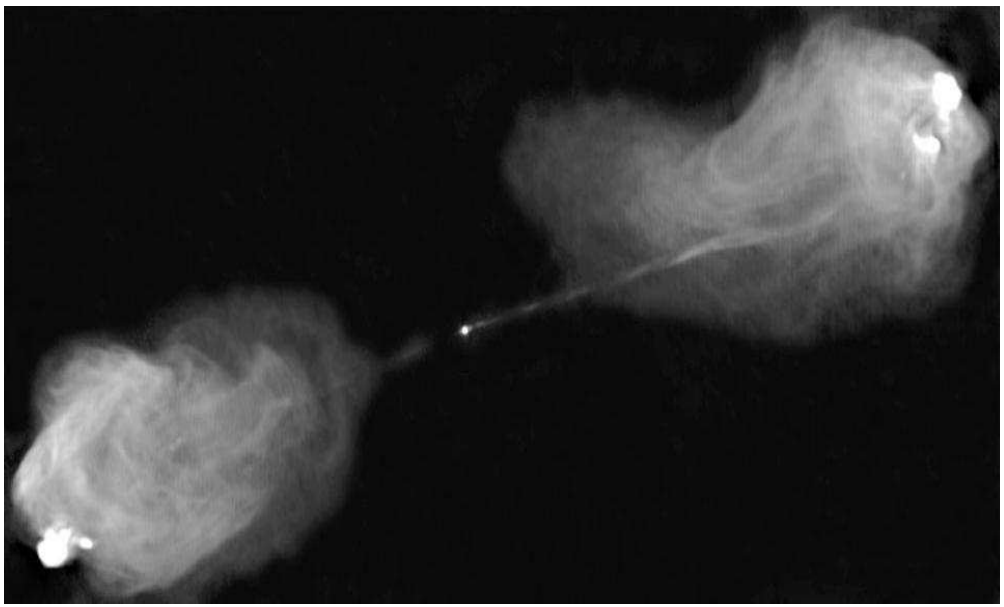
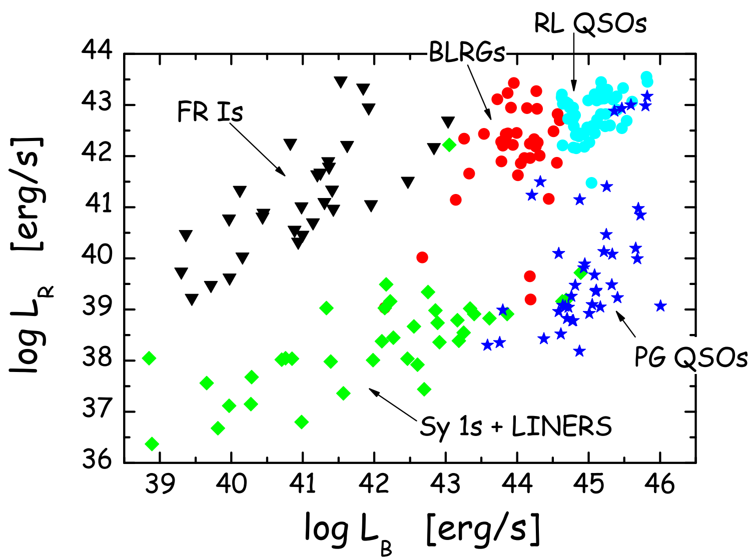
Fanaroff & Riley Dichotomy

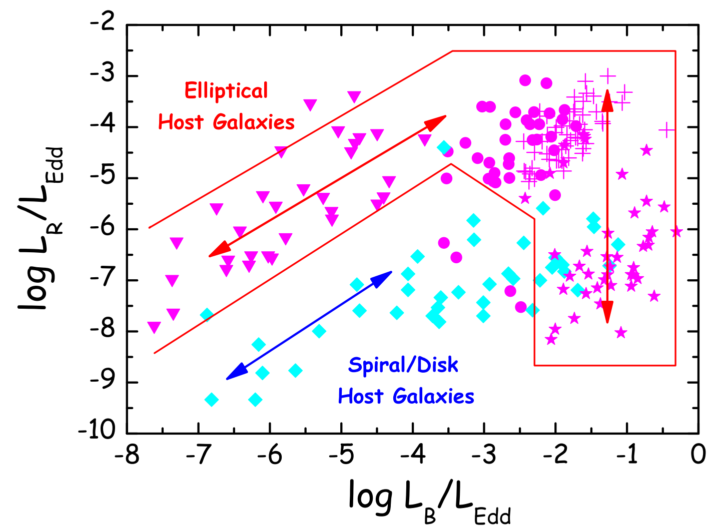


FR II (e.g., Cygnus A) and FR I (e.g., 3C 31) radio galaxies (*Fanaroff & Riley 1974, MNRAS, 167*):

- powerful $\leftrightarrow$ weak radio sources;
- edge-brightened $\leftrightarrow$ edge-darkened;
- one-sided jet & two hot-spots $\leftrightarrow$ two-sided jets & lacking hot-spots.

FR Is and Others: Jet Power vs Accretion Power

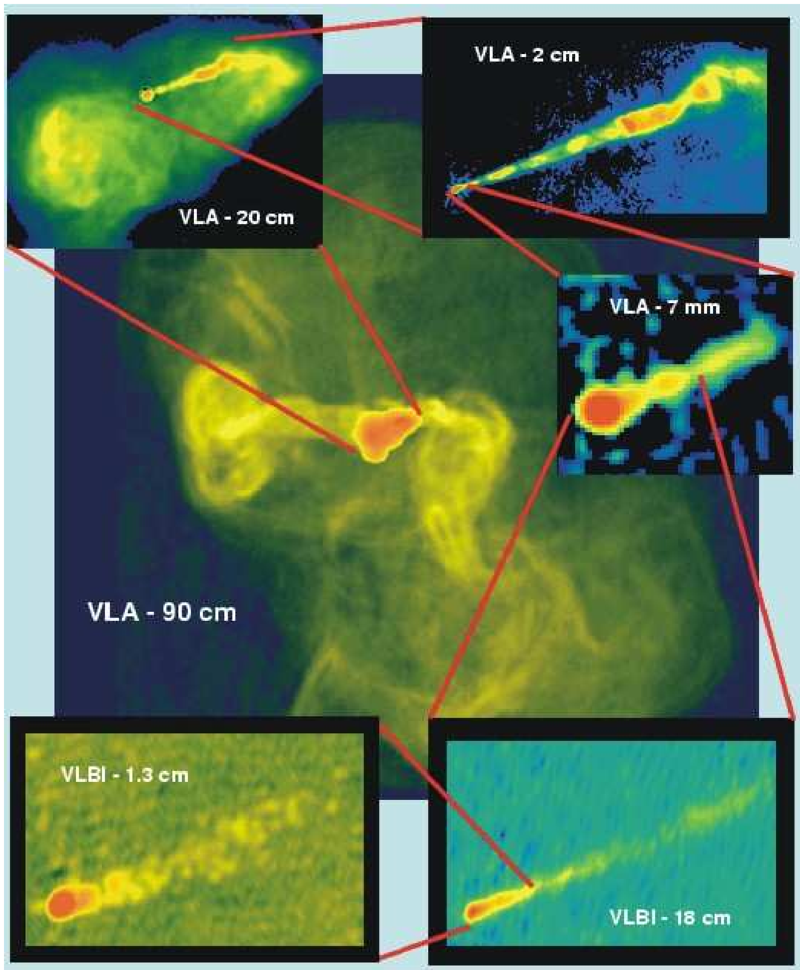




$L_{\rm R}$ — total 5 GHz luminosity; $L_{\rm B}$ — B-band nuclear luminosity;
$L_{\rm Edd}$ — Eddington lumonisty; $L_{\rm bol} \approx 10\, L_{\rm B}$ — bolometric nuclear luminosity;
$R = L_{\nu_5}/L_{\nu_B} \approx 10^5\,(L_{\rm R}/L_{\rm B})$ — radio loudness parameter

FR Is: low jet- and disk-related powers, low accretion rates, elliptical hosted.
(Sikora, Stawarz, & Lasota, ApJ submitted; astro-ph/0604095).

Large-Scale Radio Structure of M 87



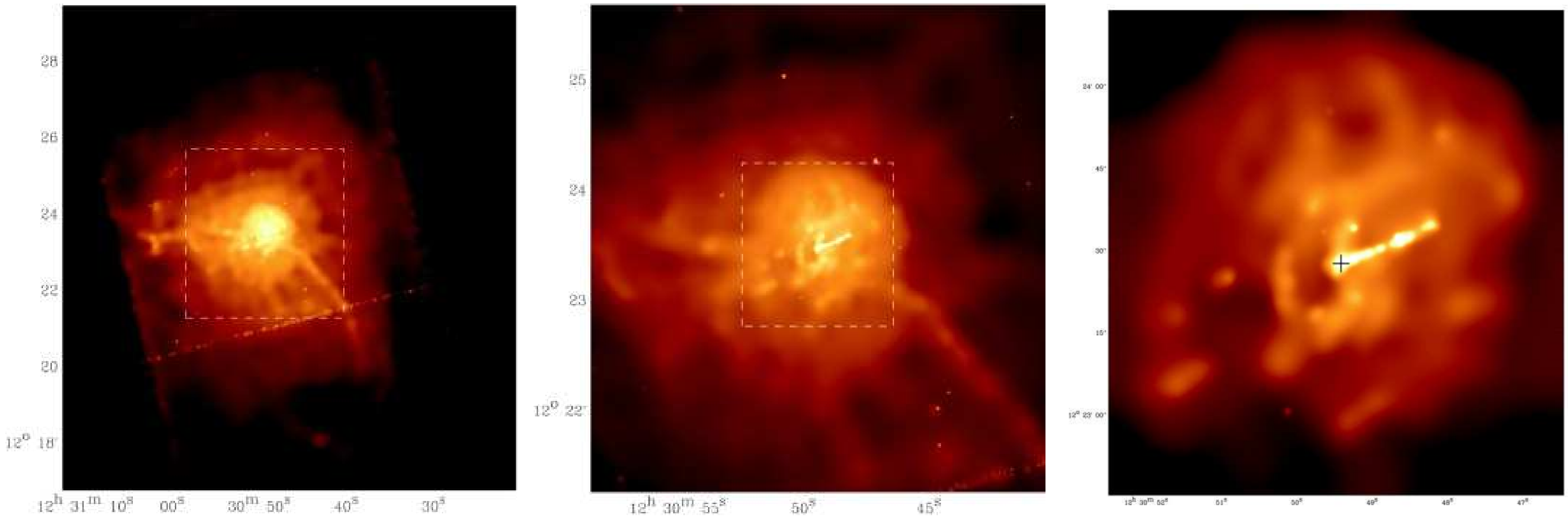
wen, NRAO, with J. Biretta, STScI, & J. Eilek, NMIMT,

Amorphous large-scale radio structure of M 87 (*Owen et al. 2000, ApJ, 543*).

"buoyant bubbles of cosmic rays (inflated by an earlier nuclear active phase of the galaxy) rise through the cooling gas (...); bubbles uplift relatively cool X-ray-emitting gas from the central regions of the cooling flow to larger distances." (*Churazov et al. 2001, ApJ, 554*)

"the jet disrupts very close to the galactic core, but the plasma flow appears to continue in a much less ordered fashion, forming giant 'bubble' which has partly mixed with the ambient thermal plasma." (*Eilek et al. 2002, New AR, 46*)

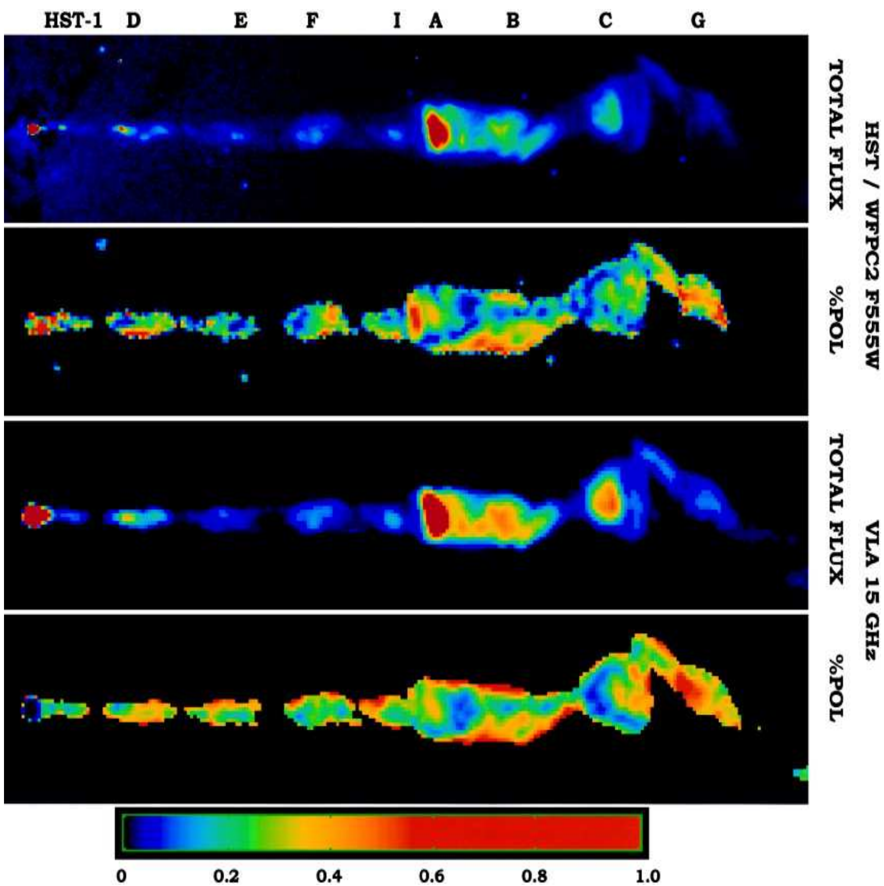
X-ray Cluster Gas Around M 87

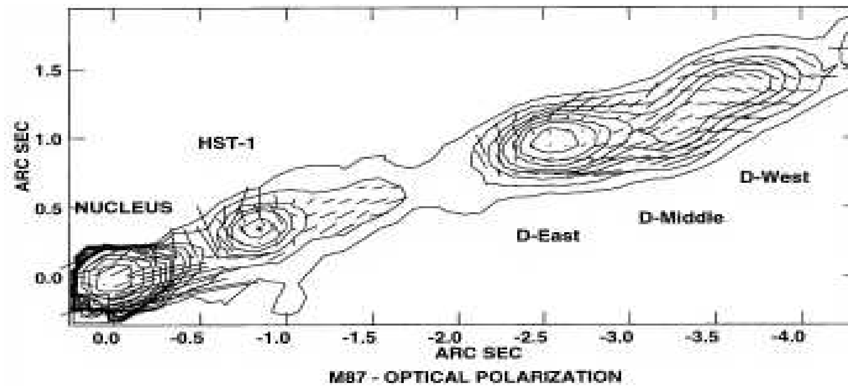


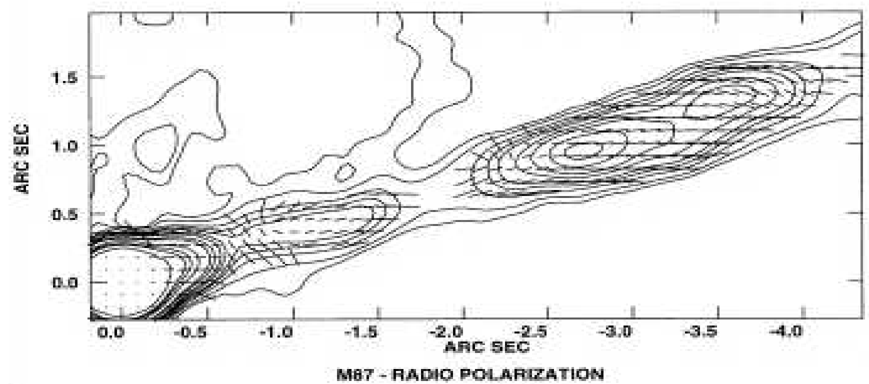
Cluster gas surrounding M 87 as observed in X-rays by the *Chandra X-ray Observatory*:

"The inner radio lobes are aligned with depressions in the X-ray surface brightness, and there is no evidence of shock heating in the X-ray emission immediately surrounding the inner radio lobes, suggesting that the radio plasma has gently pushed aside the X-ray emitting gas. (...) On larger scales the most striking feature is the X-ray arc running from the east, across the central regions of M87, and off to the southwest. The gas in the arc has at least two temperatures, is probably overpressured with respect to, and somewhat more metal-rich than, the ambient intracluster medium" (Young et al. 2002, ApJ, 579; see also Di Matteo et al. 2003, ApJ, 582; Feng et al. 2004, ApJ, 607.)

Synchrotron Emission of the M 87 Jet

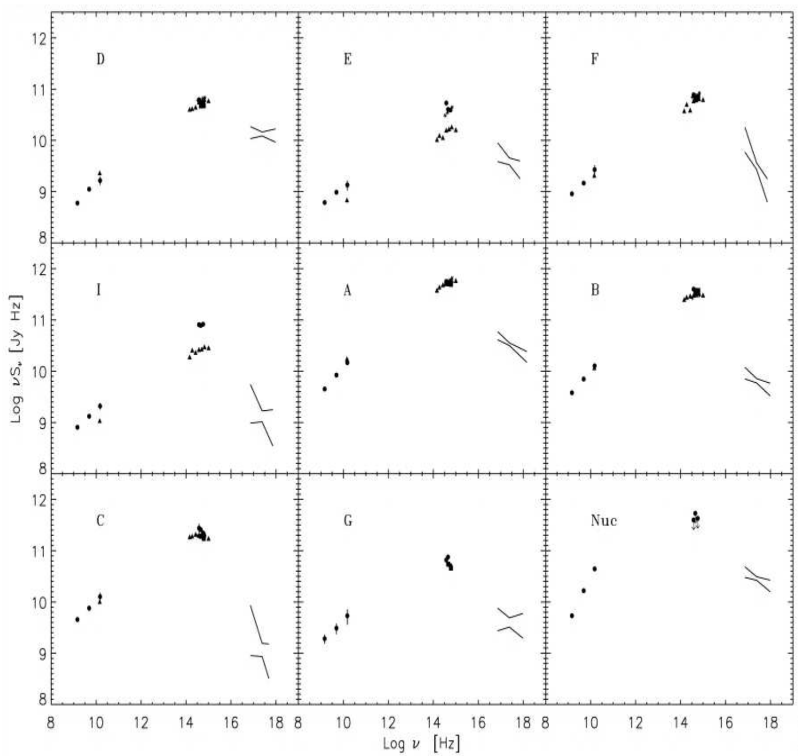






Radio and optical synchrotron emission of 2-kpc-long M 87 jet (*Perlman et al. 1999, AJ, 117*).

VHE Electrons in the M 87 Jet



Biretta et al. 1991, AJ, 101; Meisenheimer et al. 1996, A&A, 307; Sparks et al. 1996, ApJ, 473; Perlman et al. 2001, ApJ, 551; Marshall et al. 2002, ApJ, 564; Wilson & Yang 2002, ApJ, 568; Waters & Zepf 2005, ApJ, 624; Perlman & Wilson 2005,ApJ, 627.

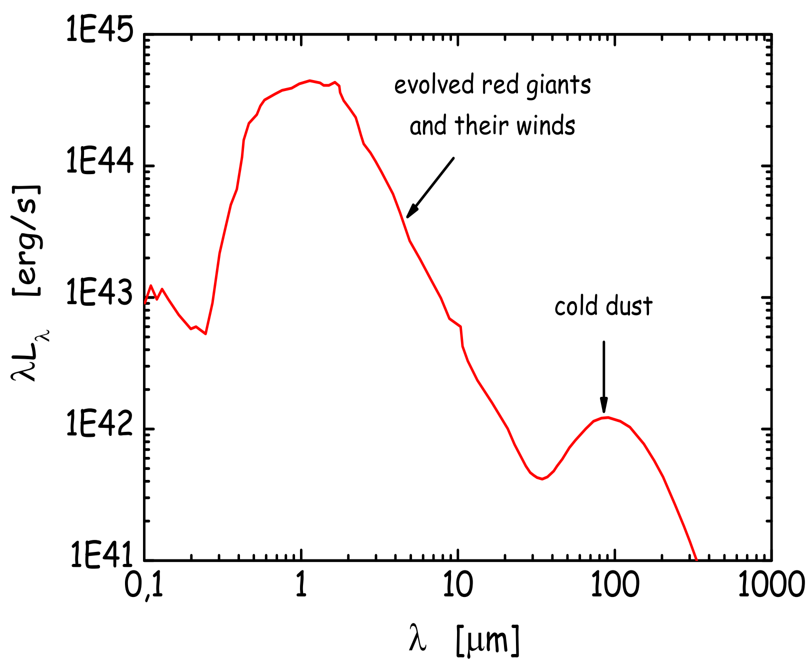
Let us reconctruct the comoving energy distribution of the electrons contributing to the observed emission of the brightest knot A (located ~ 1 kpc from the active center), $n'_{\rm e} \equiv \int n'_{\rm e}(\gamma)\, d\gamma$, from the well-constrained synchrotron continuum, and find the expected inverse-Compton emission as a function of free parameters:

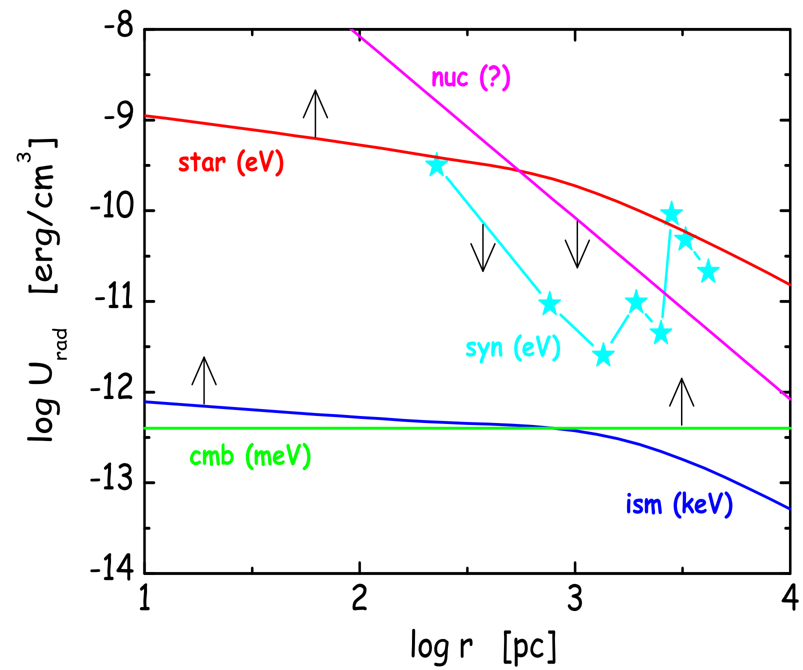
- the jet magnetic field B,
- the bulk Lorentz factor Γ,
- the jet viewing angle θ

.

(Note, that the electrons emitting $>$ eV synchrotron photons under the minimum power condition have energies $>$ TeV!)

Dominant Starlight Photon Field

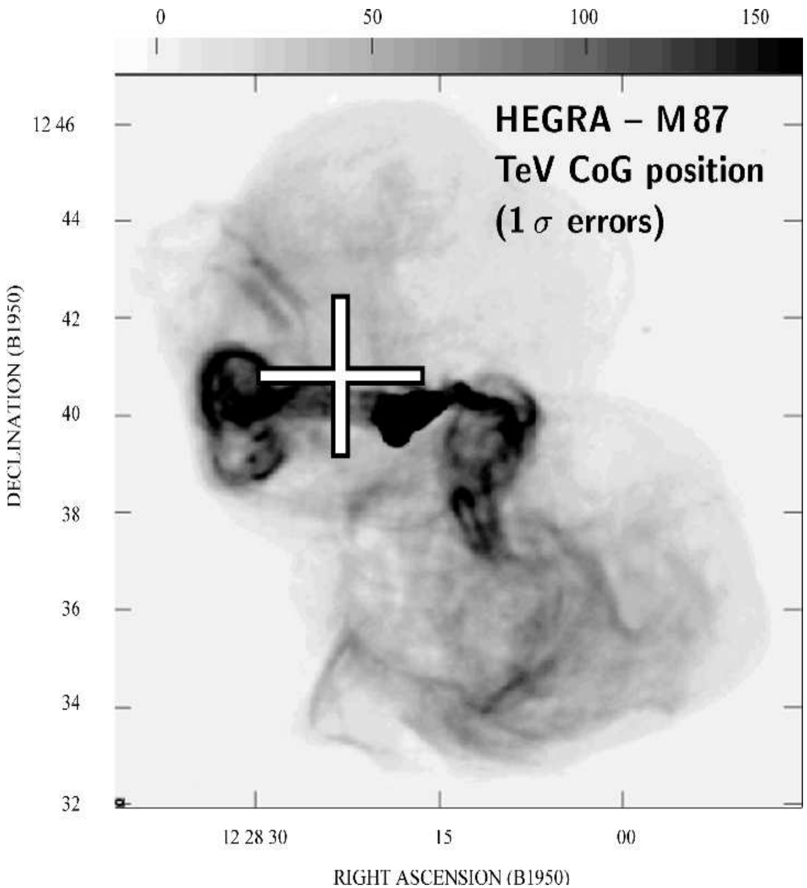




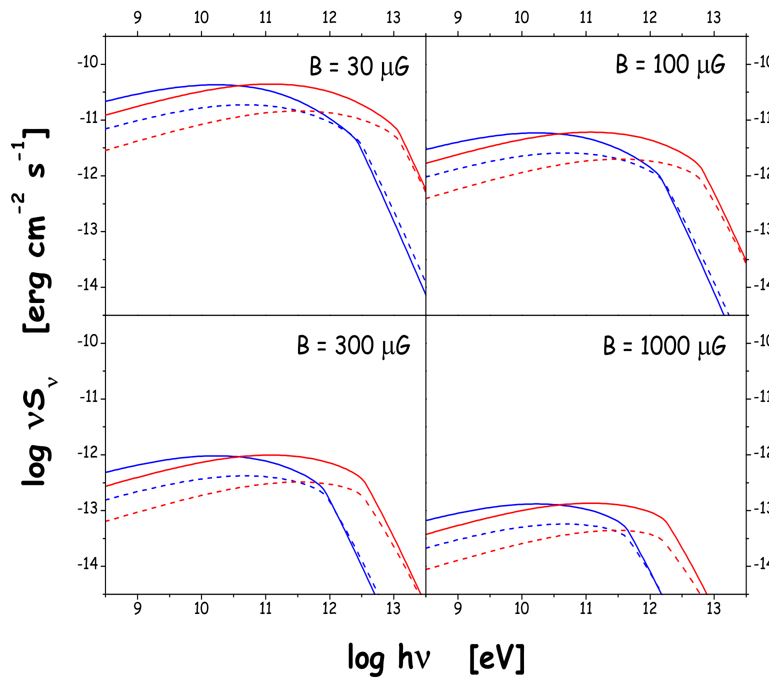
A template SED of a giant elliptical galaxy (*Silva et al. 1998, ApJ, 509*). Starlight may dominate over CMB up to >kpc distances! (This wasn't noticed before...)

Radiation fields in M87 along the jet as measured in the galactic rest frame; arrows illustrate transformation to the jet rest frame. *(Stawarz et al. 2006, MNRAS, 370)*

VHE γ-Rays from knot A?

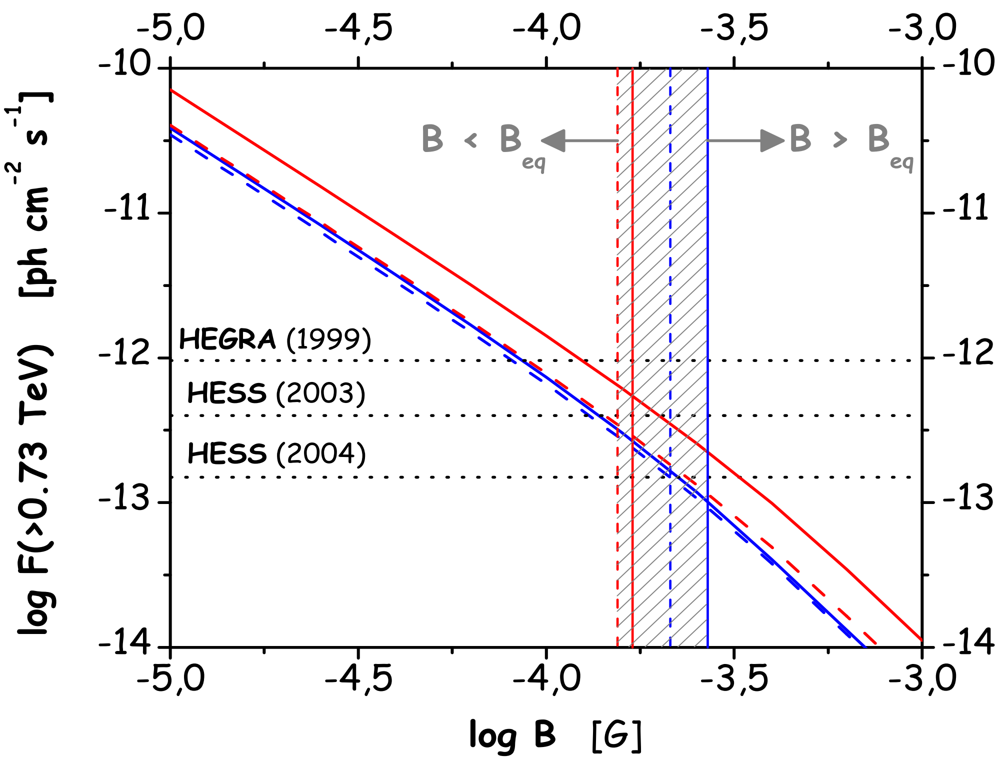


HEGRA detection of M 87 system (*Aharonian et al. 2003, A&A, 403*).



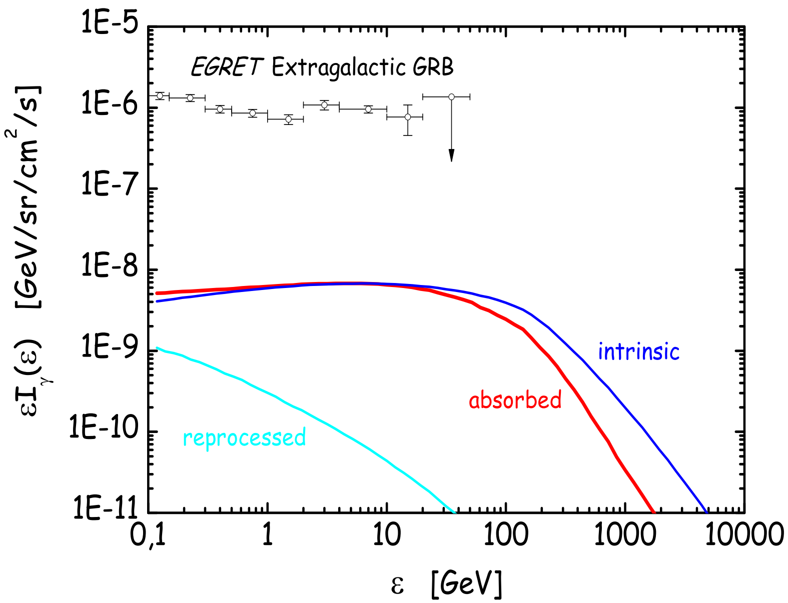
IC/STAR emission of knot A: for $\theta = 30^0$ and 20^0 (blue and red), $\Gamma = 5$ and 3 (solid and dashed), with KN regime included. *(Stawarz et al. 2005, ApJ, 626)*

Knot A in the M 87 Jet — Strong Magnetic Field



$B \geq B_{\mathrm{eq}}$ for the brightest knot A in M 87 jet in order not to overproduce the TeV emission.

Contribution of FR I Jets to GRB



Contribution of kpc-scale FR I jets to extragalctic γ-ray background as measured by *EGRET* under the minimum power condition, including absorption (on EBL) and reprocession effects.

Under the minimum power condition (corresponding to $B_{\rm eq} \sim 300\ \mu$G on average), kpc-scale FR I jets should contribute about 1% to the extragalctic γ-ray background as measured by *EGRET*. Thus, since

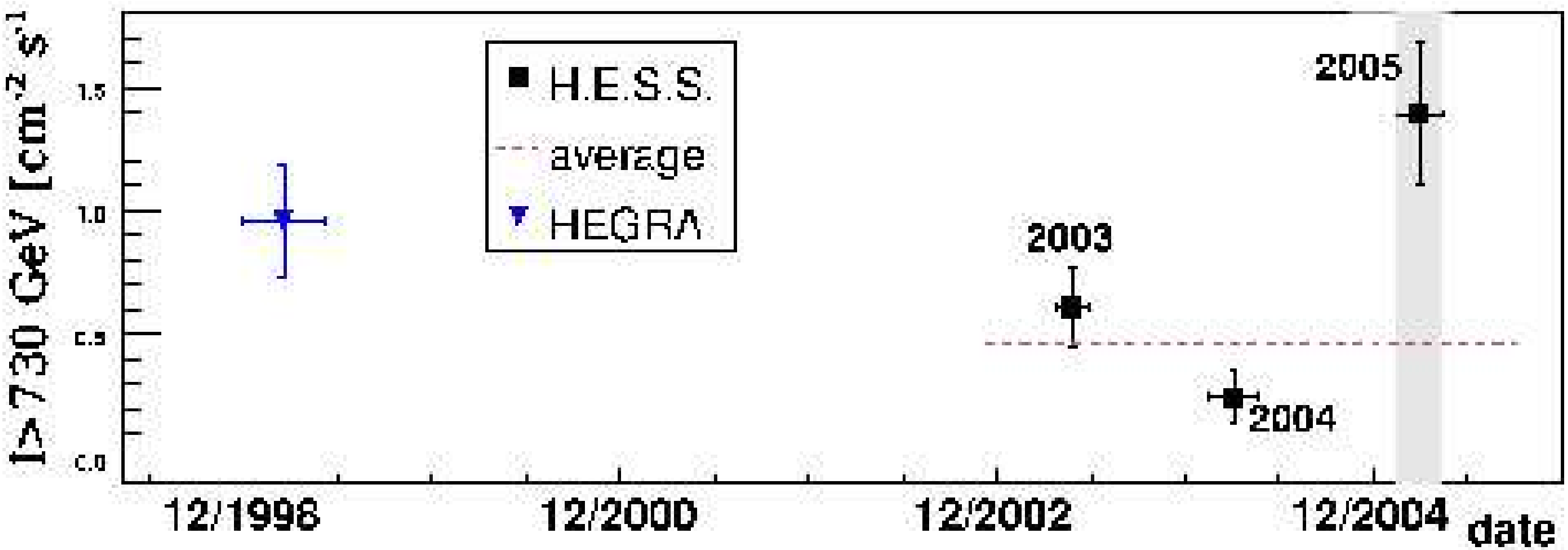
(1) $$[\varepsilon I_\gamma(\varepsilon)] \propto B^{-2}$$

(roughly!), the jet magnetic field has to be on average $B > 0.1\, B_{\rm eq}$.

GLAST can put much stronger constraints, since for $B \sim B_{\rm eq}$ the expected number of FR I jets detected in its 1-year all-sky survey is ~ 3.

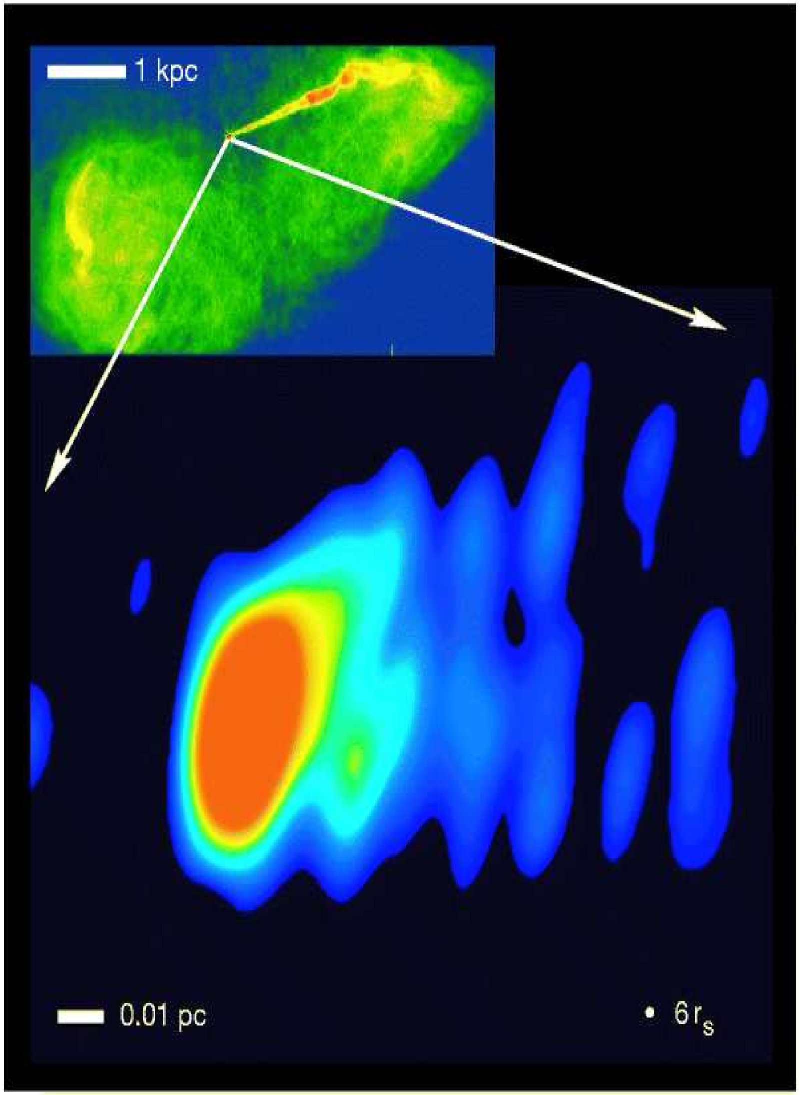
(Stawarz et al. 2006, ApJ, 637)

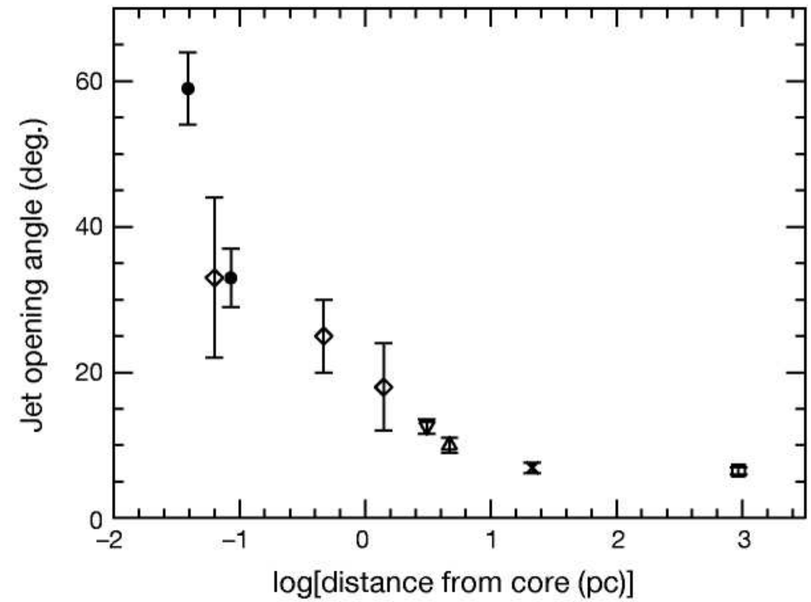
Variable TeV Emission from M 87



So what is the source of a variable (on timescales < 1 yr) TeV emission from M 87?

The Most Inner Portions of the M 87 Jet



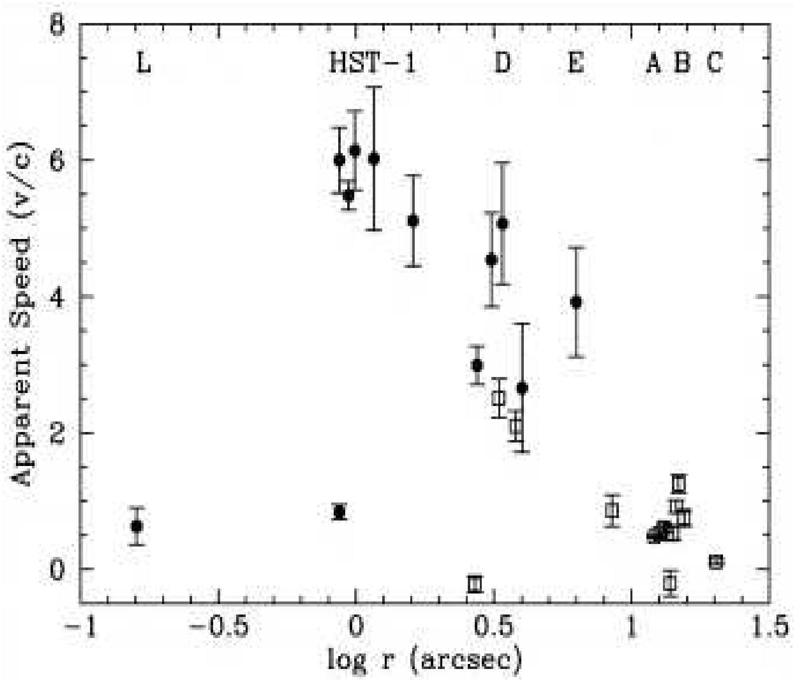


A very broad limb-brightened outflow on the scales < 0.5 mas; strong collimation at $\sim 100\ r_{\rm g} \approx 30$ mpc, continuing out to $\sim 3 \times 10^4\ r_{\rm g} \approx 10$ pc (*Junor et al. 1999, Nature, 401*).

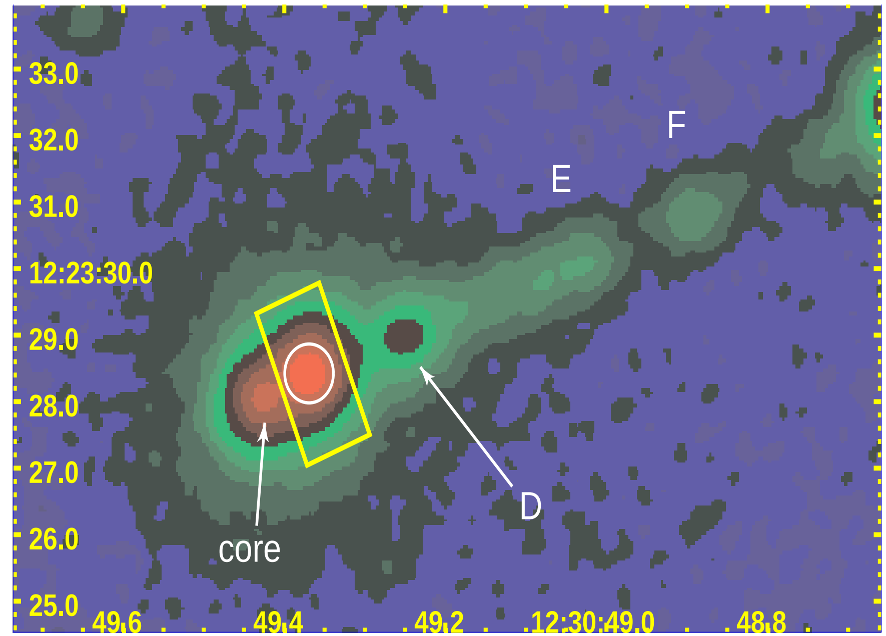
conversion:

$$r_{\rm g} = 3.85\ \mu\text{arcsec} = 0.3\ \text{mpc}$$

Elusive HST-1 knot of the M 87 Jet



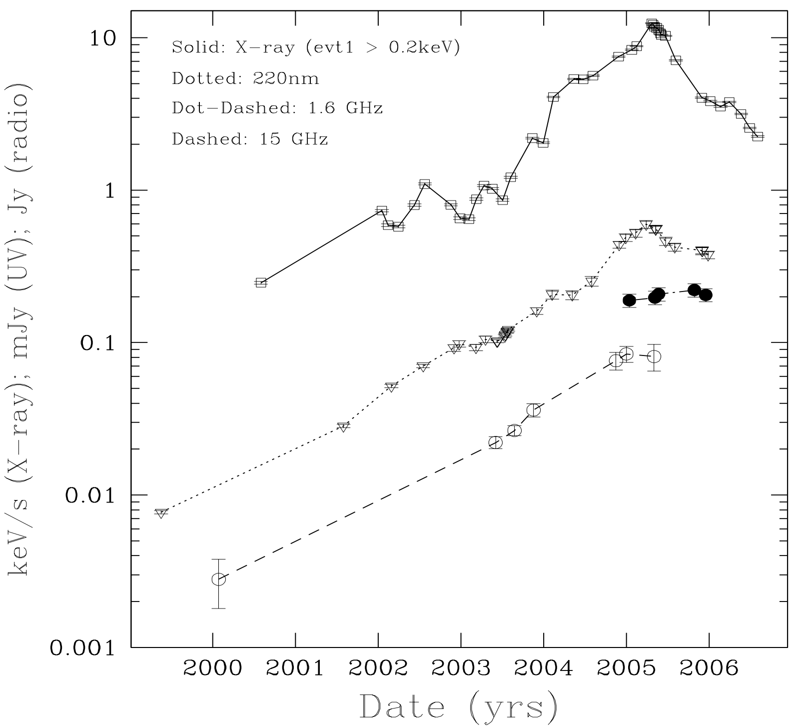
Apparent velocities in M 87 jet (*Biretta et al. 1999, ApJ, 520* and references therein).

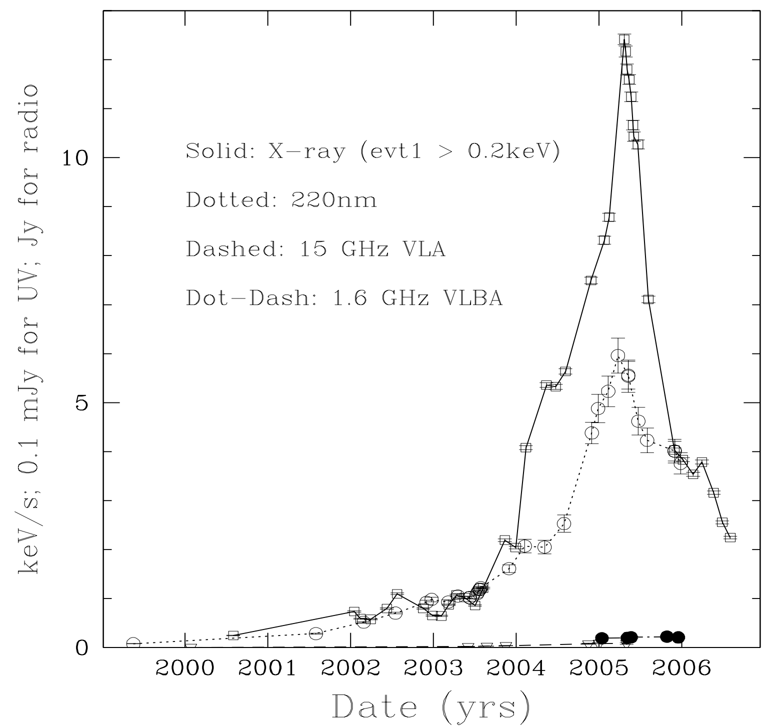


Strongly variable HST-1 knot in M 87 jet (*Harris et al., 2003, ApJ, 586; Perlman et al. 2003, ApJ, 599; Harris et al. 2006, ApJ, 640*).

<u>*Above:*</u> X-ray picture A.D. 2005.

Broad-Band Variability of the HST-1 Flaring Point





HST-1 lightcurve in 2000-2006 shows unusual synchrotron outburst in 2005 (while the core was steady).

Harris et al., 2003, ApJ, 586; Perlman et al. 2003, ApJ, 599; Harris et al. 2006, ApJ, 640

Host Galaxy Profiles — X-rays

The observed thermal X-ray surface brightness:

(2) $$\mu_{\rm X}(r) \propto \left[1+\left(\frac{r}{r_{\rm K}}\right)^2\right]^{-3\,\beta+0.5} \propto r^{-0.7} \quad \text{for} \quad r > r_{\rm K} \approx 18'' = 1.4\,{\rm kpc}$$

with $\beta = 0.4$, $r_{\rm K} = 18'' = 1.4$ kpc, and $kT_{\rm G} \lesssim 1.5$ keV for $r < 60''$ (*Boehringer et al. 2001, A&A, 365; Young et al. 2002, ApJ, 579; Di Matteo et al. 2003, ApJ, 582*).

The implied density profile of the X-ray emitting hot gas:

(3) $$\rho_{\rm G}(r) \propto \left[1+\left(\frac{r}{r_{\rm K}}\right)^2\right]^{-3\,\beta/2} \propto r^{-1.2} \quad \text{for} \quad r > r_{\rm K} \approx 18'' = 1.4\,{\rm kpc}$$

(for example, $n_{\rm e} \sim 0.15$ cm^{-3} for $r \sim 30''$ and $n_{\rm e} \sim 0.03$ cm^{-3} for $r \sim 100''$, consistently with other ellipticals).

It is not however clear if $\rho_{\rm G}(r) \propto const$ for $r < 18''$.

Host Galaxy Profiles — Optical

The observed starlight surface brightness:

(4) $$\mu_{\rm O}(r) \propto r^{-b} \quad {\rm with} \quad b = \begin{cases} 0.25 & {\rm for} \quad r < r_{\rm B} \approx 3'' = 234\,{\rm pc} \\ 1.3 & {\rm for} \quad r > r_{\rm C} \approx 7'' = 546\,{\rm pc} \end{cases} ,$$

(*Young et al. 1978, ApJ, 221; Lauer et al. 1992, AJ, 103*). The implied stellar density profile $\rho_{\rm O}(r) \propto r^{-(b+1)}$. A general property of the elliptical galaxies:

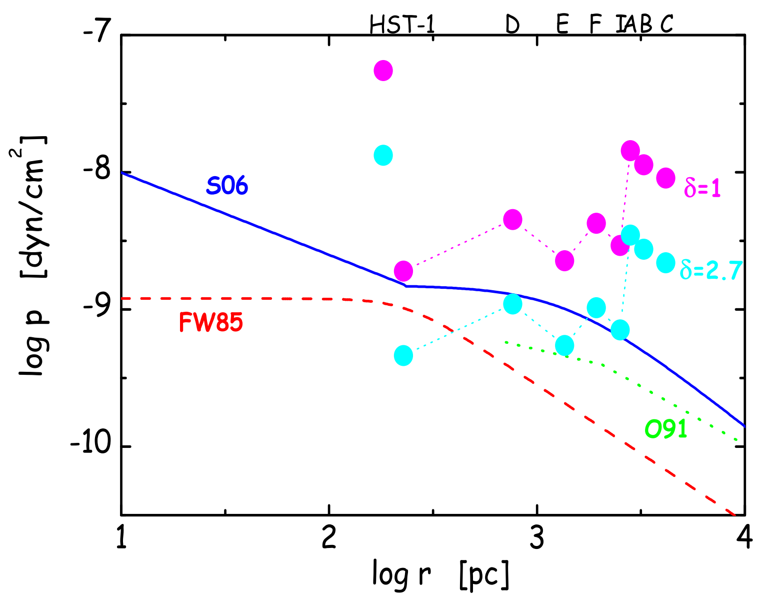
(5) $$\mu_{\rm O}(r) \propto \mu_{\rm X}(r) \quad \Rightarrow \quad \rho_{\rm S}(r) \propto \rho_{\rm G}^2(r)$$

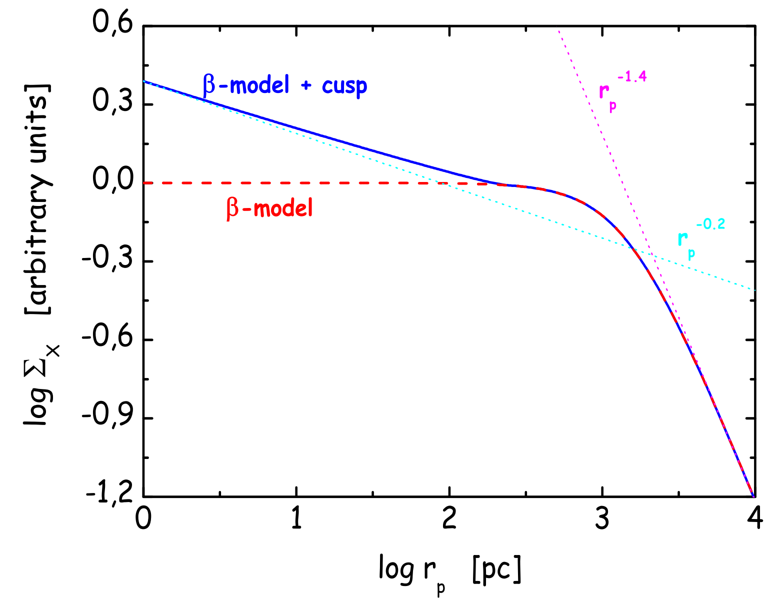
Hence, one can reconstruct the pressure of the ambient thermal medium in M 87 host galaxy as:

(6) $$p_{\rm G}(r) = p_0 \times \begin{cases} (r/r_{\rm B})^{-0.6} & {\rm for} \quad r < r_{\rm B} \approx 3'' = 234\,{\rm pc} \\ 1 & {\rm for} \quad r_{\rm B} < r < r_{\rm K} \\ (r/r_{\rm K})^{-1.2} & {\rm for} \quad r > r_{\rm K} \approx 18'' = 1,4\,{\rm kpc} \end{cases} ,$$

$p_0 = 1.5 \times 10^{-9}$ dyn cm^{-2}.

Pressure Balance





Different profiles of the hot gas pressure in M 87 host galaxy. Circles indicate $p_{\rm min}$ in jet knots, for $\delta = 1$ (filled ones), and $\delta = 2.7$ (open ones).

Normalized X-ray surface brightness (Σ_X) profiles of the M 87 host galaxy due to emission of the hot gas (*Stawarz et al. 2006, MNRAS, 370*).

Dynamics of M 87 Jet

ASSUMPTION1 : Gradual collimation of the broad innermost jet in M 87 is due to dynamically dominating magnetic field (see, e.g., *Gracia et al. 2005, A&A, 442*).

ASSUMPTION2 : Conversion to the particle flux occurs further out, e.g. at $\sim 10^3\ r_{\rm g}$ (see *Giannios & Spruit 2006, A&A, 450*). Thereby the jet starts to expand freely.

In a free particle dominated jet, gas pressure decreases very rapidly. For example, $p_{\rm j}(r) \propto r^{-2\,\hat{\gamma}} = r^{-8/3}$ for a cold plasma, and $p_{\rm j}(r) \propto r^{-2}$ in the case of ultrarelativistic gas. The ambient gas pressure in M 87 decreases as $p_{\rm G}(r) \propto r^{-\eta}$ with $\eta = 0.6$. Hence, as $\eta < 2\,\hat{\gamma}$ and $\eta < 2$, the initially free jet in M 87 certainly

- will become reconfined at some point r_0,
- will develop a reconfinement shock, and
- the reconfinement shock will reach the jet axis at some further point along the jet, $r_{\rm cr}$, where the jet itself will come to the pressure equilibrium with the external gas

(*Komissarov & Falle 1997, MNRAS, 288*).

Reconfinement Shocks

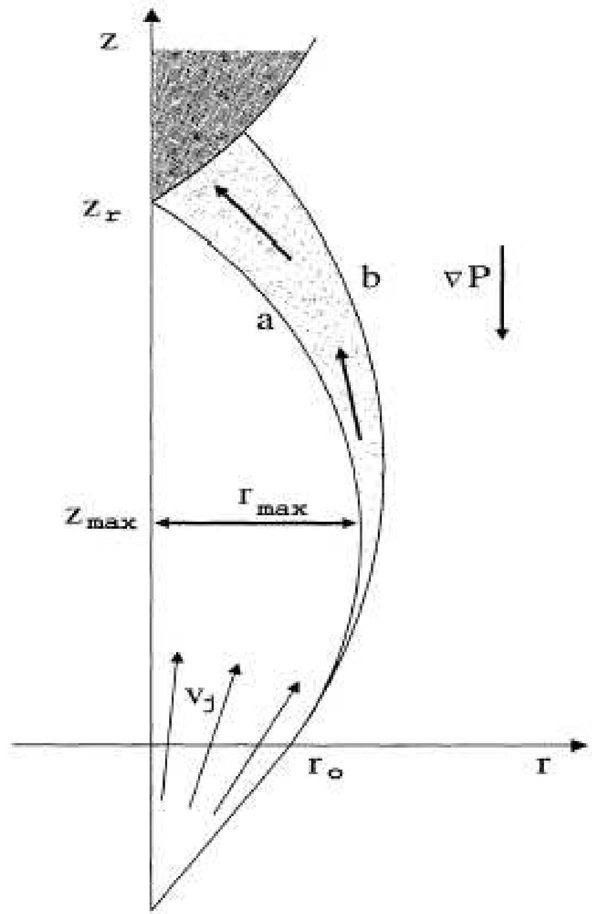


Figure 3. Reconfinement of hypersonic conical jet. (a) is the reconfinement shock, (b) is the jet boundary.

Reconfinement Shock in M 87 Jet

For a free relativistic jet dominated by the ultrarelativistic gas, jet kinetic power is

(7) $$L_{\rm j} = 4\, p_{\rm j}\, \Gamma_{\rm j}^2\, \beta_{\rm j}\, c\pi\, r^2\ \tan^2\Phi \quad ,$$

where the opening angle $\tan\Phi = 3\sqrt{2}/\Gamma_{\rm j}\beta_{\rm j}$. With the pressure profile as given above for the M 87 host, one obtains distance of the reconfinement nozzle

(8) $$r_{\rm cr} \approx \left[\frac{0.1\, L_{\rm j}}{c\, p_0\, r_{\rm B}^{0.6}}\right]^{0.7} \quad .$$

We propose that the extremely compact, stationary and overpressured HST-1 flaring point, present at the upstream edge of the HST-1 complex, is placed at $\sim\ r_{\rm cr}\ =\ 0.8''$, while the outer subcomponents of the HST-1 knot — superluminal features characterized by the minimum pressure in rough equilibrium with the surrounding medium — can be identified with the region occupied by a diverging reflected shock further away from $r_{\rm cr}$.

For the jet viewing angle $\theta = 20^0$, the jet luminosity implied by the model, $L_{\rm j} \approx 10^{44}$ erg s^{-1}, is consistent with the jet power required to feed radio lobes (*Bicknell & Begelman 1996, ApJ, 467; Owen et al. 2000, ApJ 543*).

HST-1 Knot as a TeV Source?

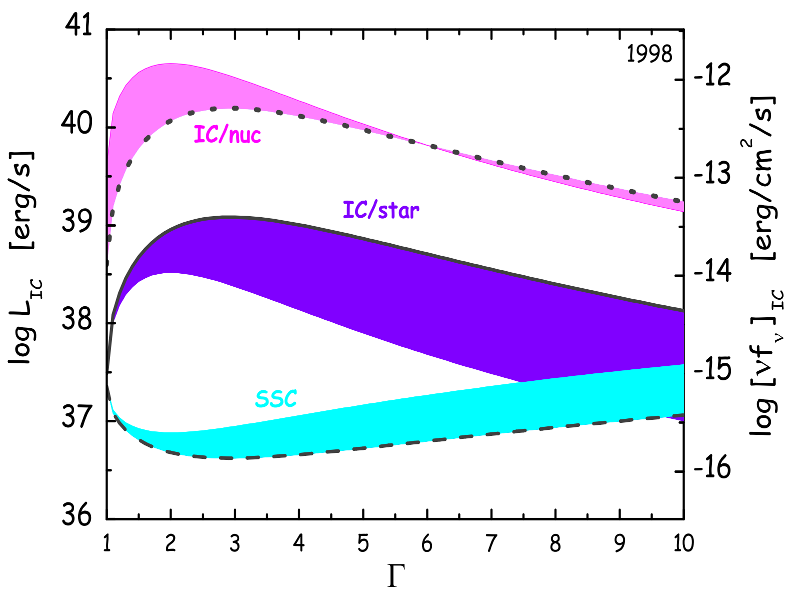
Although the reconfinement/reflected shock structure is stationary in the observer's rest frame, variations and changes in the central engine lead inevitably to flaring of this part of the outflow, in particular when the excess particles and photons emitted by the active nucleus in its high-activity epoch and traveling down the jet arrive after some time to the reconfinement nozzle. In a framework of this scenario, one should expect firstly high-energy γ-ray flare due to comptonization of the photons from the nuclear outburst, and then, after some delay

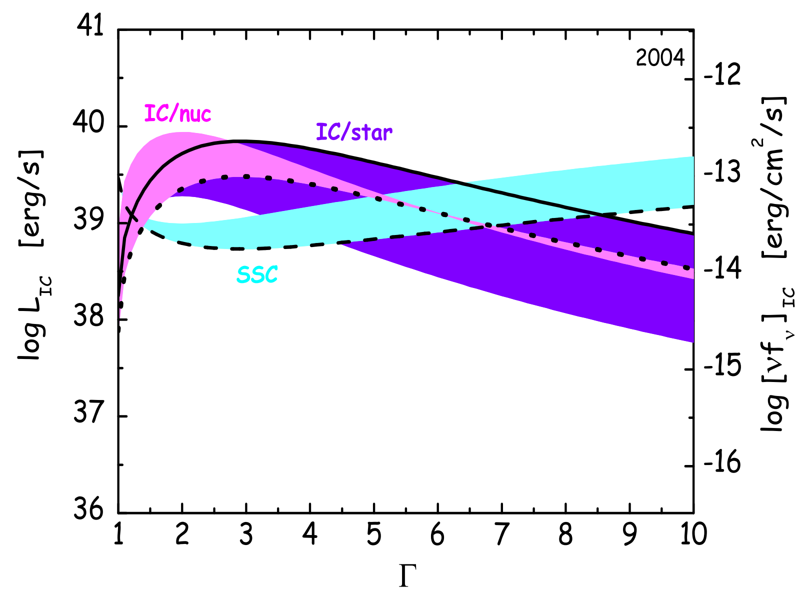
$$\Delta t \approx \frac{r}{c\,\beta_{\rm nuc}} - \frac{r}{c} \approx \frac{r_{\rm p}}{2c\,\Gamma_{\rm nuc}^2\,\sin\theta} \sim 100\,(\sin\theta)^{-1}\,\Gamma_{\rm nuc}^{-2} \quad {\rm yr} \tag{9}$$

(where $r_{\rm p} = r\,\sin\theta = 62.4$ pc is a projected distance of the HST-1 flaring region from the core), synchrotron flare due to excess nuclear particles shocked at the nozzle. This delayed synchrotron flare could be accompanied by the subsequent inverse-Compton brightening due to upscattering of the ambient radiation fields by the increased population of the ultrarelativistic particles.

For example, $\Delta t \sim 6$ yr between presumable maximum of the TeV emission (1998/1999) and the observed maximum of the synchrotron emission of the HST-1 knot (2005) is consistent with $\theta \sim 20^0$ and $\Gamma_{\rm nuc} \sim 7$.

The Expected TeV Fluxes





Expected TeV emission of the HST-1 flaring region in 1998 and 2004, for $\theta = 20^0$ and different bulk velocities of the emitting plasma. Shaded regions indicate the appropriate luminosity ranges for $\theta = 20^0 - 30^0$.

The expected fluxes (assuming energy equipartition between radiating electrons and the jet manetic field) are consistent with observations (*Stawarz et al. 2006, MNRAS, 370*).

Large-Scale Radio Structure of Cen A

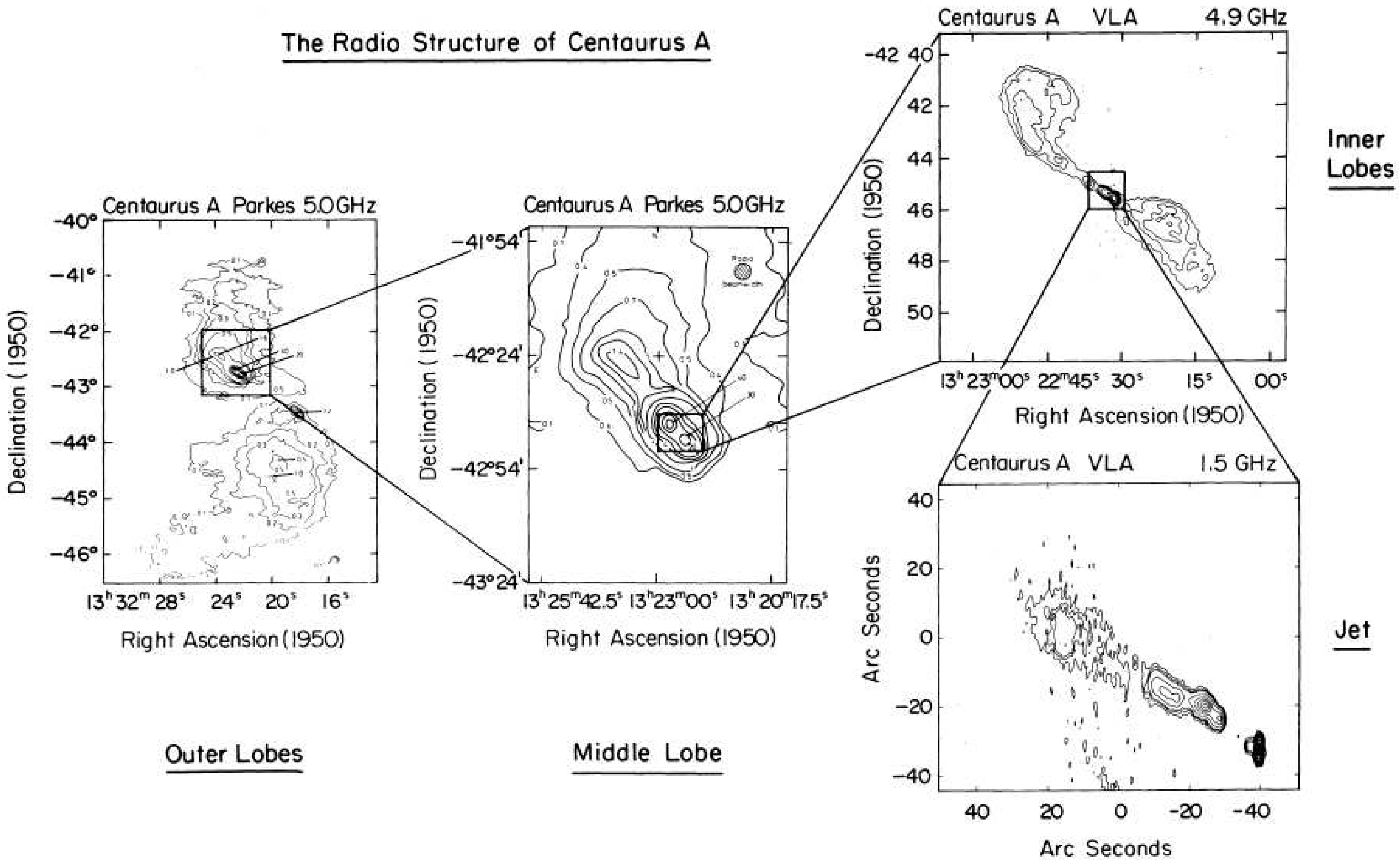
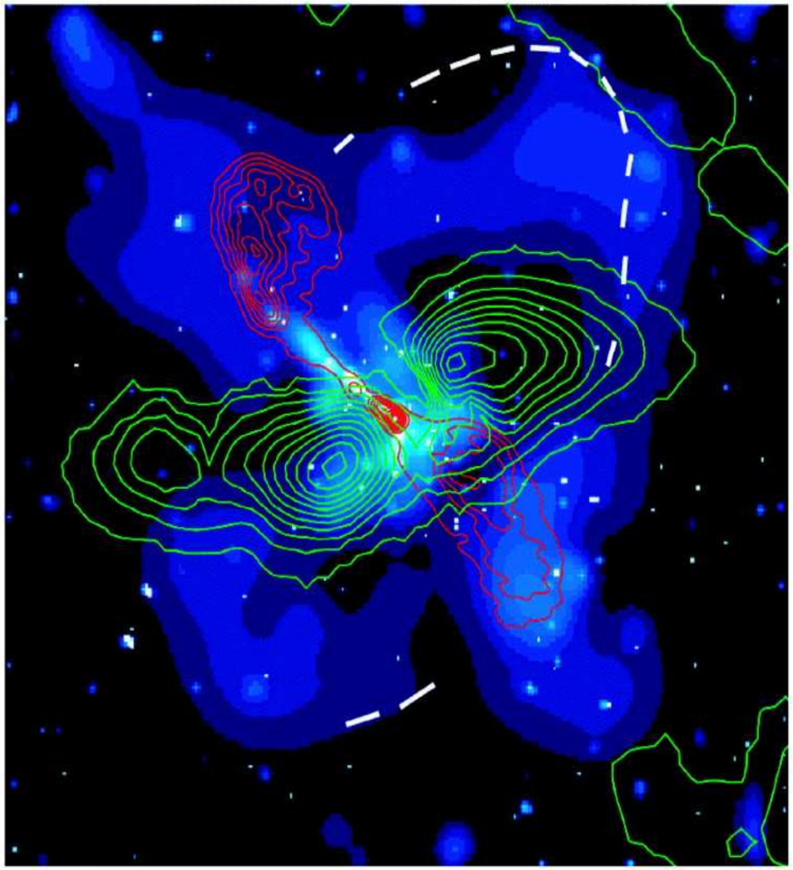


FIG. 11.—An illustration of the different scale sizes of radio structure in Cen A. The Parkes maps of the outer lobes and middle lobe were kindly provided by R. Ekers from a paper by Haynes, Cannon, and Ekers (1982). The inner lobes map is reproduced from Fig. 2, and the jet map is reproduced from Fig. 3.

Merger History of Cen A



X-rays (blue), 21 cm radio continuum (red contours), 21 cm line H I (green contours) (*Karovska et al. 2002, ApJ, 577*).

$d = 3.4$ Mpc, for which 1″ corresponds to 16 pc, and 1′ to 0.96 kpc.

Famous 'dark lane' pronounced within the host elliptical body, being in fact an edge-on disk of rotating metal-rich stars, nebulae, dust clouds, H II regions, OB associations, and supernova remnants, is most probably remnant of the merger with spiral galaxy, which happened some $10^8 - 10^9$ *years ago (see Israel 1998, ARA&A, 8).*

Radio and X-ray synchrotron jet in Cen A: a very complex jet morphology with filaments and diffuse sub-structured knots; limb-brightened radio and X-ray profiles; projected magnetic field parallel to the jet axis (see Schreier et al. 1979, 1981; Burns et al. 1983, Clarke et al. 1986, 1992; Kraft et al. 2002; Hardcastle et al. 2003).

Starlight Photon Field in Cen A

Starlight surface brightness in elliptical galaxies are typicaly well fitted by a Nuker law

(10) $$I(r) = I_{\rm b}\, 2^{(b-d)/a} \left(\frac{r}{r_{\rm b}}\right)^{-d} \left[1 + \left(\frac{r}{r_{\rm b}}\right)^{a}\right]^{-(b-d)/a} ,$$

where r is the distance from the galactic nucleus. For Cen A host galaxy $a = 1.68$, $b = 1.3$, $d = 0.1$, and the break radius $r_{\rm b} = 2.56'' = 41$ pc (*Capetti & Balmaverde, 2005, A&A, 440*). The starlight emissivity is $j(r) \propto r^{-1}\, I(r)$, and the monochromatic V-band galactic luminosity is

(11) $$L_{\rm V} = 4\pi \int_{\mathcal{V}} [\epsilon j_{\epsilon}(\xi)]_{\rm V}\; d\mathcal{V} = 10^{43.82} \quad {\rm erg/s} \quad ,$$

where $\xi \equiv r/r_{\rm b} \leq 375$ and $\epsilon \equiv \varepsilon/m_{\rm e}c^2$ is the starlight photon energy ε in $m_{\rm e}c^2$ units. The differential photon number density, $n(\epsilon, \Omega)$, is then

(12) $$n(\epsilon, \Omega) = \frac{\epsilon^{-2}}{m_{\rm e}c^3} \int [\epsilon j_{\epsilon}(\xi)]\; dl \quad .$$

This allows to find precisely attenuation of nuclear γ-ray flux along the host elliptical.

Photon-Photon Annihilation

Optical depth for photon-photon annihilation, computed for the case of monodirectional beam of γ-ray photons with dimensionless energy ϵ_γ, propagating through the stellar photon field of the host galaxy from the active center up to the terminal distance $r_{\rm t}$, is

$$\tau(\epsilon_\gamma) = \int_0^{r_{\rm t}} dr \int dn \, (1 - \varpi) \, \sigma_{\gamma\gamma} \quad , \tag{13}$$

where ϖ is the cos function of the angle between the γ-ray photon and the incident starlight photon, $dn = n(\epsilon, \Omega) \, d\epsilon \, d\Omega$ is the differential starlight photon number density, and

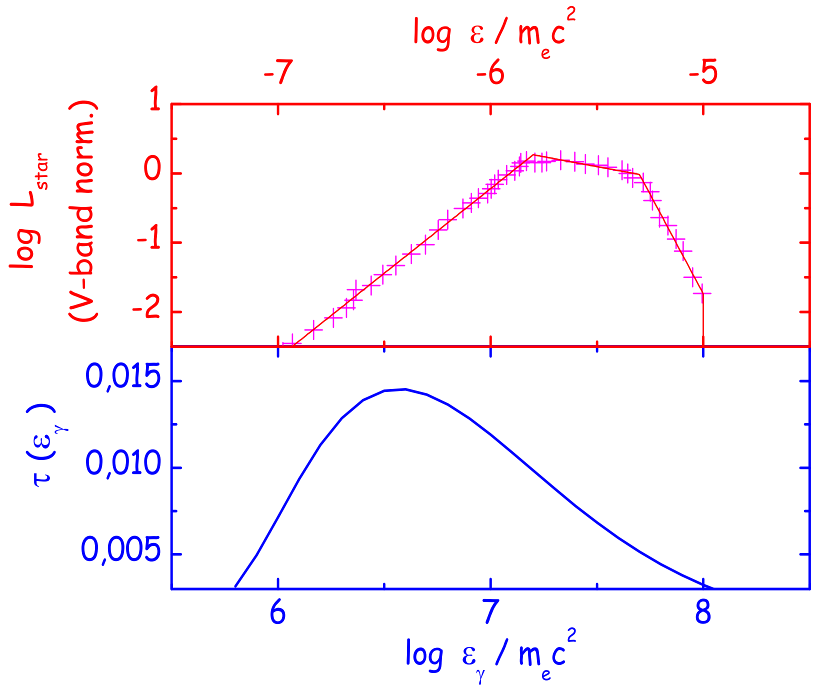
$$\sigma_{\gamma\gamma}(\epsilon_\gamma, \epsilon, \varpi) = \frac{3\sigma_{\rm T}}{16} \, (1 - \beta^2) \, \left[(3 - \beta^4) \, \ln \left(\frac{1 + \beta}{1 - \beta} \right) - 2\beta \, (2 - \beta^2) \right] \tag{14}$$

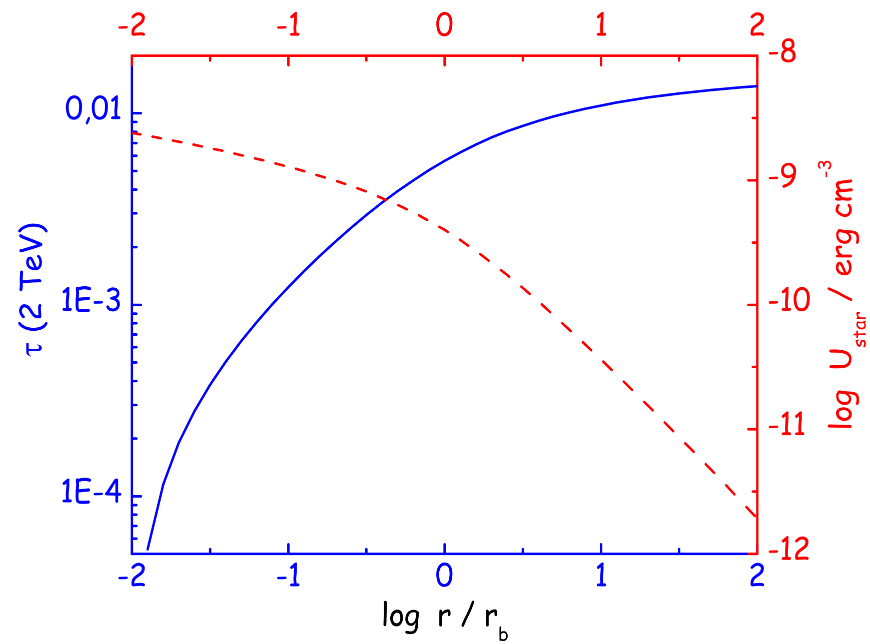
is the photon-photon annihilation cross section, where

$$\beta \equiv \left(1 - \frac{2}{\epsilon_\gamma \epsilon \, (1 - \varpi)} \right)^{1/2} \quad , \tag{15}$$

is the velocity of the created electron/positron.

The Optical Depth





About 1% of the TeV flux produced by active nucleus is inevitably absorbed by the stralight ...

... within central $100\,r_{\rm b}$ of elliptical host (*Stawarz et al. 2006, MNRAS, 371*).

How Much Can It Be For Cen A?

We are interested in the total, time-averaged and angle-averaged (i.e., ‘calorimetric’) flux of TeV photons produced by the active nucleus and ‘injected’ into the host galaxy. Assuming quite standard apectral index $\alpha_\gamma = 1$, the relation between the integrated photon flux and the monochromatic flux energy density at any photon energy $\varepsilon \geq \varepsilon_0$ is simply $[\varepsilon S_\varepsilon] = [\varepsilon_0 \, F(> \varepsilon_0)]$. This flux is related to the emitting fluid (jet) intrinsic monochromatic power (assumed to be isotropic in the jet comoving frame) radiated in a given direction, $\partial L'/\partial\Omega' = L'/4\pi$, by the expression

(16) $$[\nu S_\nu] = \frac{1}{d_{\rm L}^2} \, \frac{\delta_{\rm nuc}^3}{\Gamma_{\rm nuc}} \, \frac{\partial L'}{\partial \Omega'} = \frac{1}{d_{\rm L}^2} \, \frac{\delta_{\rm nuc}^3}{\Gamma_{\rm nuc}} \, \frac{L'}{4\pi} \quad ,$$

where $\Gamma_{\rm nuc}$ and $\delta_{\rm nuc} = \Gamma_{\rm nuc}^{-1} \left(1 - \sqrt{1 - \Gamma_{\rm nuc}^{-2}} \cos\theta\right)^{-1}$ are, respectively, Lorentz and Doppler factors of the nuclear portion of the jet, and θ is the jet viewing angle. On the other hand, the total power radiated into the ambient medium, being of interest here, is

(17) $$L_{\rm inj} = \oint \frac{\delta_{\rm nuc}^3}{\Gamma_{\rm nuc}} \, \frac{\partial L'}{\partial \Omega'} \, d\Omega = \frac{1}{2} \, L' \, \Gamma_{\rm nuc}^{-1} \int_0^\pi \delta_{\rm nuc}^{-3} \, \sin\theta \, d\theta = L' \quad .$$

Hence, $L_{\rm inj} = 4\pi \, d_{\rm L}^2 \, \Gamma_{\rm nuc} \delta_{\rm nuc}^{-3} \, [\varepsilon_0 \, F(> \varepsilon_0)]$.

Quite A Lot!

With the HESS photon flux $F(> 0.19\,\mathrm{TeV}) < 5.68 \times 10^{-12}$ ph cm^{-2} s^{-1} (corresponding to the few-arcmin-integration area centered on the Cen A nucleus) one obtains the upper limit for the total injected monochromatic power $L_{\rm inj} < 2.4 \times 10^{39}\,\Gamma_{\rm nuc}\delta_{\rm nuc}^{-3}$ erg s^{-1}. With the prefered values $\theta \sim 50\,\mathrm{deg} - 80\,\mathrm{deg}$ inferred from the VLBI radio observations, and $\Gamma_{\rm nuc} \sim 10$ widely considered as a typical value for the bulk Lorentz factor of sub-parsec scale AGN jets, this reads as

$$L_{\rm inj} < 10^{42} - 10^{43} \quad \mathrm{erg\,s^{-1}} \quad . \tag{18}$$

The postulated here nuclear γ-ray emission is expected to be Doppler-boosted within the narrow cone characterized by the opening angle $\Gamma_{\rm nuc}^{-1} \lesssim 6\,\mathrm{deg}$. Therefore, when viewed from $\theta \geq 50\,\mathrm{deg}$, it is strongly Doppler hidden. If the observer would be located however within the beaming cone of this emission, then he would detect the flux corresponding to the isotropic luminosity

$$L(0) = (\delta^3_{\mathrm{nuc},\,\theta=0}/\Gamma_{\rm nuc})\,L' \approx \Gamma_{\rm nuc}^2\,L' < 10^{44} - 10^{45} \quad \mathrm{erg\,s^{-1}} \quad . \tag{19}$$

Such values are not in conflict with luminosities observed from the TeV-detected BL Lac objects.

Pairs in the Elliptical Host

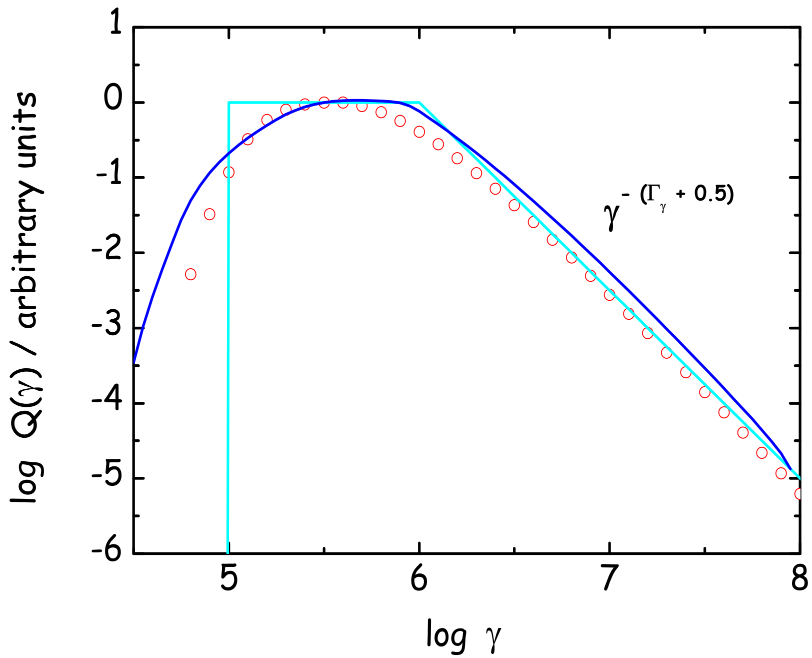
Ultrarelativistic electron-positron pairs injected to the elliptical host by photon-photon annihilation process are quickly isotropised by the galactic magnetic field. This results in creation of an istropically-emitting giant (galactic-scale) pair halo around nuclear source of beamed TeV radiation.

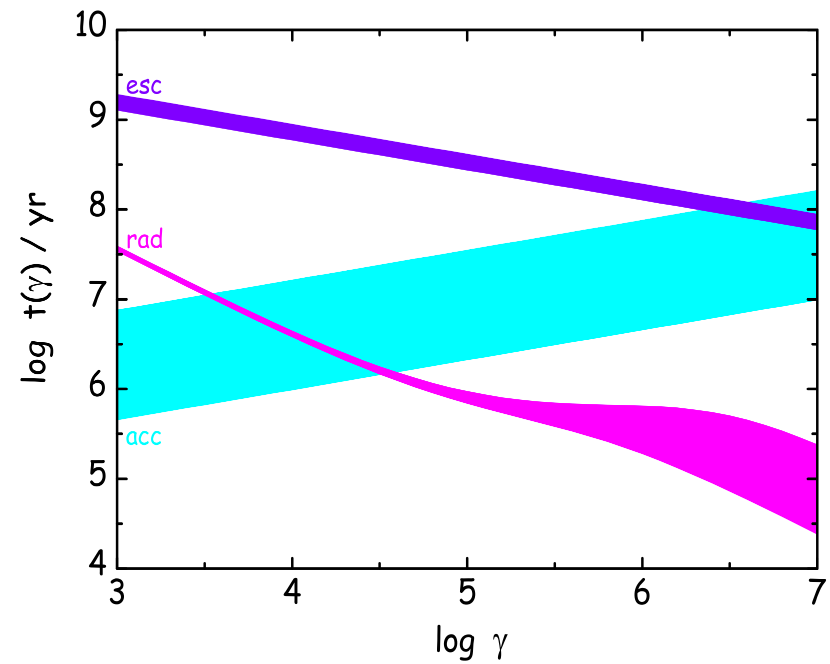
We take the characteristic values for the NGC 5128 elliptical host's magnetic field $B_{\rm gal} \approx 3-10\,\mu$G, assuming that it consists solely of the (Alfvénic) turbulent component with the maximum wavelength $\lambda_{\rm max} \sim 100$ pc and Kolmogorov energy spectrum $W(k) \propto k^{-q}$, where $q = 5/3$ (*Moss & Shukurov 1996, MNRAS, 279*). The mean free path of the created electron-positron pairs for resonant interactions with the turbulent Alfvèn modes, is then

(20) $$\lambda_{\rm e} \approx r_{\rm g} \left(\frac{\lambda_{\rm max}}{r_{\rm g}}\right)^{q-1} = r_{\rm g}^{1/3}\,\lambda_{\rm max}^{2/3} \sim 0.82 \times \gamma_6^{1/3}\,B_{-5}^{-1/3}\,{\rm pc} \quad ,$$

where $\gamma_6 \equiv \gamma/10^6$, $r_{\rm g} \equiv \gamma\, m_{\rm e} c^2/eB_{\rm gal} \sim 5.5 \times 10^{-5}\,\gamma_6\,B_{-5}^{-1}$ pc is the electrons' gyroradius, and $B_{-5} \equiv B_{\rm gal}/10\,\mu$G.

Injected Electrons





Pair production rate for the photon spectrum of primary γ-ray photons $n_\gamma(\epsilon_\gamma) \propto \epsilon_\gamma^{-\Gamma_\gamma}$ is $\quad Q(\gamma) \propto \gamma^{-\Gamma_\gamma}\,\tau\,(2\,\gamma)$.

$t_{\rm iso} \sim 3\,\lambda_{\rm e}/c \sim 10\,\gamma_6^{1/3}\,B_{-5}^{-1/3}$ yrs,

$t_{\rm esc} \sim 3\,R^2/\lambda_{\rm e}\,c \sim 10^8\,\gamma_6^{-1/3}\,B_{-5}^{1/3}$ yrs,

$t_{\rm acc} \sim \beta_{\rm A}^{-2}\,t_{\rm iso} \sim 10^{6.5}\,\gamma_6^{1/3}\,B_{-5}^{-7/3}$ yrs

Electrons' Evolution

The resulting electron energy distribution, $n_{\rm e}(\gamma)$, ignoring re-acceleration and escape effects, can be found from the continuity equation

(21) $$\frac{\partial n_{\rm e}(\gamma)}{\partial t} = \frac{\partial}{\partial \gamma} \{ |\dot{\gamma}|_{\rm cool} \, n_{\rm e}(\gamma) \} + Q(\gamma) \quad ,$$

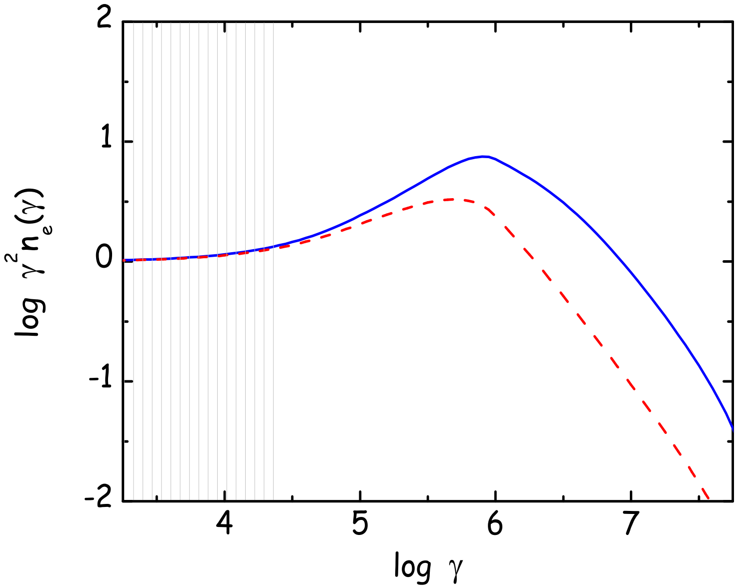
where $Q(\gamma)$ denotes injection of high-energy electrons through photon-photon annihilation, and $|\dot{\gamma}|_{\rm cool} = |\dot{\gamma}|_{\rm syn} + |\dot{\gamma}|_{\rm ic}$ is the total rate of the radiative cooling.

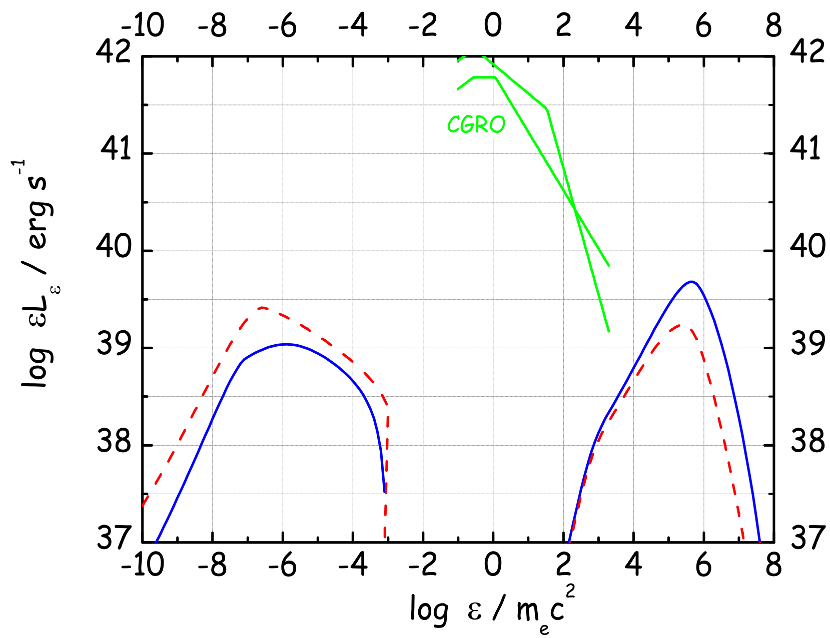
(22) $$|\dot{\gamma}|_{\rm syn} = \frac{4 \, c \sigma_{\rm T}}{3 \, m_{\rm e} c^2} \, U_{\rm B} \, \gamma^2 \quad , \quad \text{and} \quad |\dot{\gamma}|_{\rm ic} = \frac{4 \, c \sigma_{\rm T}}{3 \, m_{\rm e} c^2} \, U_{\rm B} \, \gamma^2 \, q \, F_{\rm KN} \quad ,$$

where $q \equiv \langle U_{\rm rad} \rangle / U_{\rm B} \approx 7 \, B_{-5}^{-2}$, and $F_{\rm KN} = \frac{1}{\langle U_{\rm rad} \rangle} \int \frac{U_{\epsilon}}{(1+4 \, \gamma \, \epsilon)^{1.5}} \, d\epsilon$. The steady-state solution is then

(23) $$n_{\rm e}(\gamma) = \frac{3 \, m_{\rm e} c}{4 \, \sigma_{\rm T}} \, \frac{\int_{\gamma} d\gamma' \, Q(\gamma')}{\gamma^2 \, U_{\rm B} \, (1 + q \, F_{\rm KN})} \quad .$$

Electron and Emission Spectra





High-energy pile-up bump due to decreased cooling rate in KN regime. This results in distinctive spectral shape of the halo's emission.

Inverse-Compton scattering of the starlight photon field by istropic pair halo in Cen A can be detected by *GLAST* and modern *IACTs*!

Conclusions

- Large-scale (> 0.1 kpc) jets in FR I radio galaxies are able to produce high energy and very high energy γ-ray emission.
- Analysis of this emission offers possibility for estimating several unknown and crucial jet parameters like jet magnetic field, jet bulk velocity, etc.
- In analyzing high energy emission of FR I sources one has to consider not only internal structure of their outflows, but also properties of their elliptical hosts.
- If M 87 and Cen A are representative for other FR I and BL Lac sources, then one should expect different jet components and different emission processes contributing to the observed γ-ray emission (instead of a widely assumed homogeneous one-zone 'blazar' emission zone with pure SSC radiation).
- And indeed, recently, *HESS Cherenkov Telescope* has detected distant ($z > 0.1$) BL-Lacs with steady TeV fluxes. When correcting for the Extragalactic Background Light absorption, one can find that they are intrinsically powerful and very flat-spectrum at VHE γ-ray frequencies (e.g., *Katarzyński et al. 2006, MNRAS, 368*). Possibly already away from the 'blazar sequence'! In general, these and many other recent observations challenge 'standard' models for TeV-emitting BL Lacs. Understanding M 87, Cen A and other nearby FR I jets can help to understand these objects.

TeV-Emitting BL Lacs Away from the Blazar Sequence