Modelling the high energy gamma-ray component of the nearest radio galaxy, Centaurus A

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Overview

AGN and Jets

Supermassive black holes (SMBHs) in Galaxies

- SMBHs at centre of almost all known galaxies
- a few percent of these BHs are "active"
- "active" $\rightarrow$ luminous centres — may out-shine entire galaxy

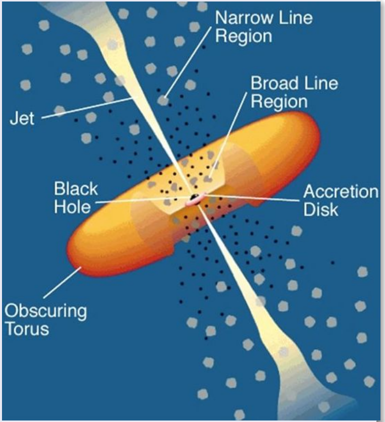
Jets from AGN — Collimated outflows

- a few percent of AGN eject radio-emitting jets
- jets with relativistic charged particles

Powering source

- BH & accretion $\rightarrow$ rotation & accretion-disk $\rightarrow$ radiation

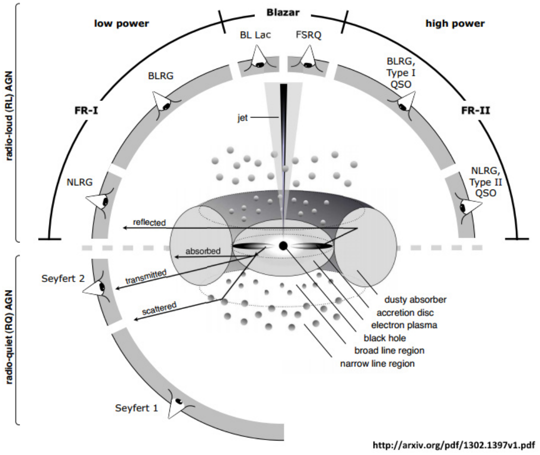
Active Galactic Nuclei
Morphology



- central supermassive black hole
- accretion disk from angular momentum (*few*ld across)
- jet of relativistic particles
- surrounding clouds: BLRs and NLRs
- dusty tous
- types of AGN: based on viewer-source alignment
- blazars, **radio galaxies**, Seyferts, quasars, etc.

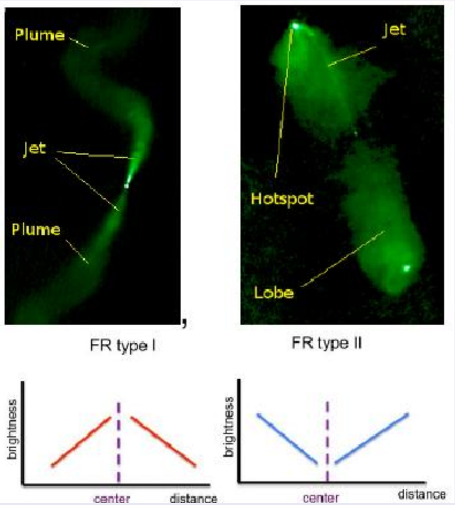
AGN Classification Scheme

Determination by Jet Viewing Angle



Radio Galaxy Classification Scheme

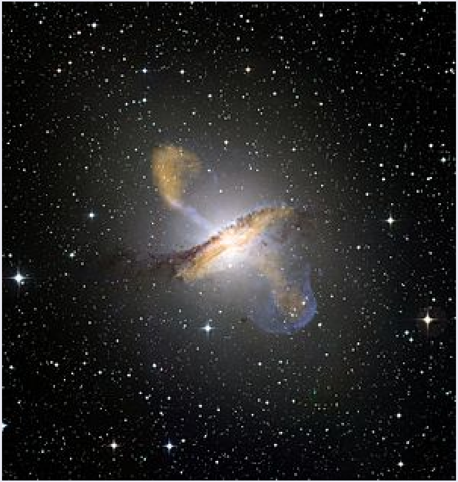
Fanaroff-Riley Classification



- morphology of double structure
- jets, lobes and hotspots
- by Fanaroff & Riley (FR) in 1974
- division on *radio* structures
- FR I: edge-darkened
- FR I e.g. Centaurus A
- FR II: edge-brightened
- RGs seen in VHE seem to be FR I
- Cen A, M 87, NGC 1275, PKS 0625-354, IC 310, Per A

Cen A: Typical Radio Galaxy (NGC 5128)

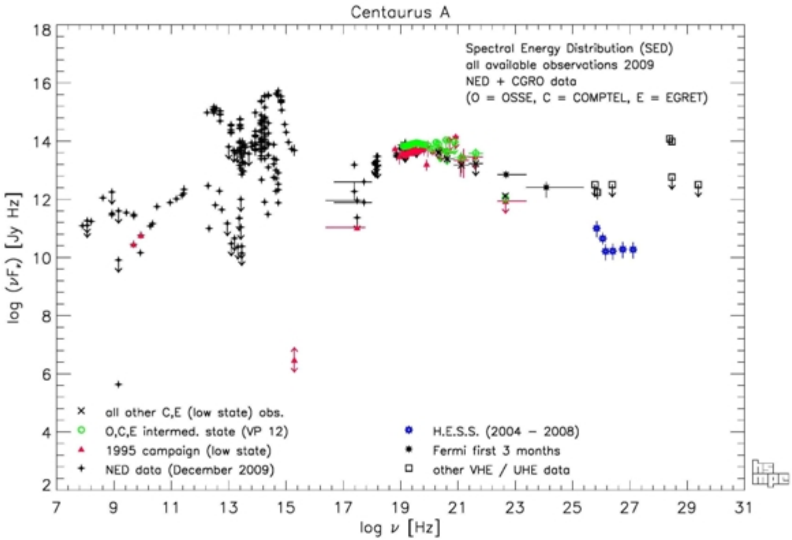
Closest AGN



- giant elliptical host galaxy NGC 5128
- discovery of NGC 5128: in 1826 by James Dunlop (Parramatta Observatory)
- FR I type radio galaxy
- closest AGN to us 16×10^6 ly ($z = 0.00183$)
- host $55 \times 10^6\ \mathrm{M}_\odot$ black hole
- jets 10^6 ly in length
- $\sim 15^\circ < \theta_{\rm view} < \sim 50^\circ$
- detected in all wavelengths: radio to VHE γ-rays

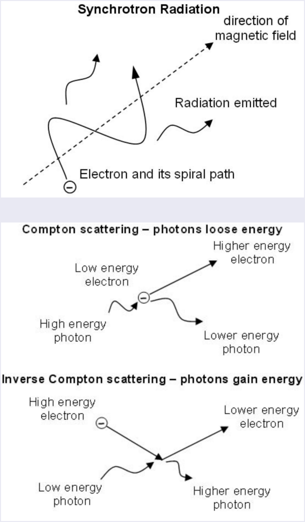
Cen A: Multi-wavelength observed SED

Data in the NASA/IPAC EXTRAGALACTIC DATABASEA (incl. H.E.S.S. data)



Radiative Processes

Emission Mechanism



Courtesy of Jeff Stanger

Various ways of producing photons

- focus: non-thermal processes
- all types of bremsstrahlung not discussed
- synchrotron radiation
- Compton: photon looses energy
- inverse-Compton: photon gains
- Synchrotron Self-Compton (SSC)
- external-Compton (EC)
- leptonic (electron-based) models
- other models: hadronic (proton-based), lepto-hadronic

Leptonic Models

Setting Electron Energy Distribution

- electron Lorentz factors: $\gamma_{\min} < \gamma < \gamma_{\max}$
  where $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ and $\beta = v/c$
- electron speeds with turn-over at a break point γ_{brk}
- most acceleration mechanisms yield power-law or log-parabola electron distributions

Motion of Emission Region

Bulk Motion

- a zone of emission region ("blob") travel at *bulk* velocity β_Γ in jets
- bulk Lorentz factor of emission region Γ
- if the emission is quasi-isotropic (in rest frame of the emission region) then the emission is beamed into a cone of opening angle $1/\Gamma$
- observed quantities are *boosted* by the Doppler Factor δ:

$$\delta = \frac{1}{\Gamma(1 - \beta_\Gamma \cos\theta_{\rm obs})}$$

- δ modifies amongst others: *photon energies*, *time*$^{\rm var}$ *scales*, *fluxes*, ...
- for example:

$$\begin{aligned} \nu_{\rm obs} &= \delta\, \nu_{\rm emm} \\ \Delta t^{\rm var}_{\rm obs} &= \frac{\Delta t^{\rm var}_{\rm emm}}{\delta} \geqslant \frac{R}{c\,\delta} \\ F^{\rm obs}_{\nu^{\rm obs}} &= \delta^3\, F^{\rm emm}_{\nu^{\rm emm}} \end{aligned}$$

Synchrotron Emission

Electrons Around Magnetic Fields

- electrons of num-density $n_e(\gamma)$ gyrate around magnetic fields in jets
- relativistic version of cyclotron motion
- accelerating charged particles radiate $\Rightarrow$ synchrotron radiation
- synchrotron emissivity:

$$j_\nu^{\rm syn} = \frac{4}{9}\left(\frac{e^2}{m_e c^2}\right)^2 u_B \sqrt{\frac{\nu}{\nu_0^3}}\, n(\gamma)$$

  where u_B is the magnetic energy density, while ν_0 is defined through the critical frequency $\nu_c = \frac{3eB}{4\pi m_e c}\gamma^2 = \nu_0\,\gamma^2$, and $j_\nu^{\rm syn}$ is based on the *delta-function approximation* $\delta(\nu - \nu_c)$.
- at low ν, synchrotron self-absorption becomes important

Synchrotron Self-Compton Radiation

Boosting Locally Produced Photons

- inverse-Compton upscattering of low-energy photons by electrons
- photon energy: $E = h\nu$ for frequency ν: normalize $\epsilon = \frac{E}{h\nu}$
- upscattered photon exits interaction with $\epsilon_s \simeq \gamma^2 \epsilon$
- process require some form of target photon field $n_{ph}(\epsilon)$
- Compton emissivity:

$$j_\nu^{\text{head-on, iso}}(\epsilon_s) = \frac{h\epsilon_s}{4\pi} \int_1^\infty d\gamma\, n_e(\gamma) \int_0^\infty d\epsilon\, n_{ph}(\epsilon) g(\epsilon_s, \epsilon, \gamma)\,,$$

where

$$g(\epsilon_s, \epsilon, \gamma) = \frac{c\pi r_e^2}{2\gamma^4 \epsilon}\left(\frac{4\gamma^2\epsilon_s}{\epsilon} - 1\right) \quad \text{if} \quad \frac{\epsilon}{4\gamma^2} \le \epsilon_s \le \epsilon\,,$$

and

$$g(\epsilon_s, \epsilon, \gamma) = \frac{2c\pi r_e^2}{\gamma^2 \epsilon}\left[2q \ln q + (1+2q)(1-q) + \frac{(4\epsilon\gamma q)^2}{(1+4\epsilon\gamma q)} \frac{(1-q)}{2}\right]$$

$$\text{if} \quad \epsilon \le \epsilon_s \le \frac{4\epsilon\gamma^2}{1+4\epsilon\gamma}\,,$$

where

$$q = \frac{\epsilon_s}{4\epsilon\gamma^2\left(1 - \frac{\epsilon_s}{\gamma}\right)}\,.$$

SSC ... to External Compton Radiation

Boosting External Seed Photons

- **seed photon option 1**: immediate synchrotron produced photons
- termed Synchrotron Self-Compton (SSC) emission
- **seed photon option 2**: pick up photons from other sources
- possible other sources: accretion disk, BLRs, dusty torus, CMB, and combinations
- disk photons: can directly be upscattered by jet electrons **or** can in from scattering off the BLR
- accretion-disk radiation can be represented as local black-body

$$\boxed{R_S = \frac{2GM_{\mathrm{BH}}}{c^2}} \qquad \boxed{T^4(r) = \frac{3R_{\mathrm{S}}L_{\mathrm{disk}}}{16\pi\sigma_{SB}r^3}\left[1 - \sqrt{\frac{3R_S}{r}}\right]}$$

with Schwarzschild radius R_S, Stefan-Boltzmann constant σ_{SB}.

Gamma-gamma Absorption

Pair Production: $\gamma + \gamma \rightarrow e^+ + e^-$

- mutual interaction of gamma-ray photons with energies ϵ_1 and ϵ_2
- electron-positron (e^+e^-) production (gamma-rays are absorbed)
- for head-on interactions we get the simplified $\gamma\gamma$ cross-section as

$$\sigma_{\gamma\gamma} = \frac{1}{3}\,\sigma_T\,\epsilon_1\;\delta(\epsilon_1 - \frac{2}{\epsilon_2})$$

  the δ-function approximation $\delta(\epsilon_1 - \frac{2}{\epsilon_2})$ is derived from strong peak of $\sigma_{\gamma\gamma}$ as function of $\epsilon_1\epsilon_2(1-\cos\theta)$ where θ is the interaction angle.
- the $\gamma\gamma$ opacity for absorption of ϵ_1 in photon field $n_{ph}(\epsilon_2, \Omega : x)$ over path length ℓ is (for solid angle Ω)

$$\tau_{\gamma\gamma} = \int_0^1 dx \int (1-\cos\theta)d\Omega \int_{2/(\epsilon_1(1-\cos\theta))}^{\infty} \sigma_{\gamma\gamma}\, n_{ph}\, d\epsilon_2$$

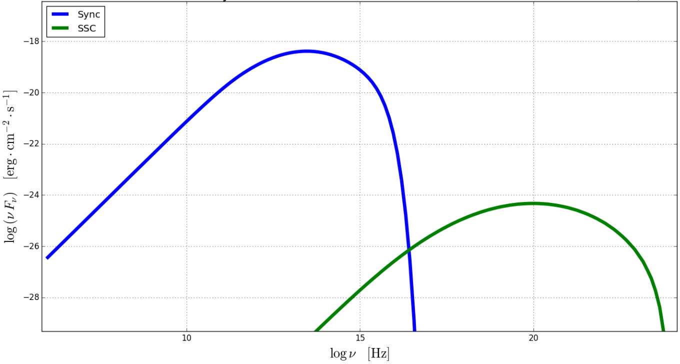
- observed flux reduced relative to emitted: $F_{\mathrm{obs}} = F_{\mathrm{emm}}\, e^{-\tau_{\gamma\gamma}}$

Synchrotron and SSC

Spectrum: Distribution of light as function of frequency

INPUT PARAMETERS

```
Jet Features                        | Electrons
    * R = 5e15 cm                   |    * num density = 1.0e-3 cm^-3
    * z = 3.1e-2                    |    * gamma_min = 1.0e2
    * Lorent factor = 7             |    * gamma_max = 1.0e4
    * theta view = 30 degrees       |    * distro = log-parabolic
    * B = 4.0 G                     |    * r = 1.5, p = 2.5
```

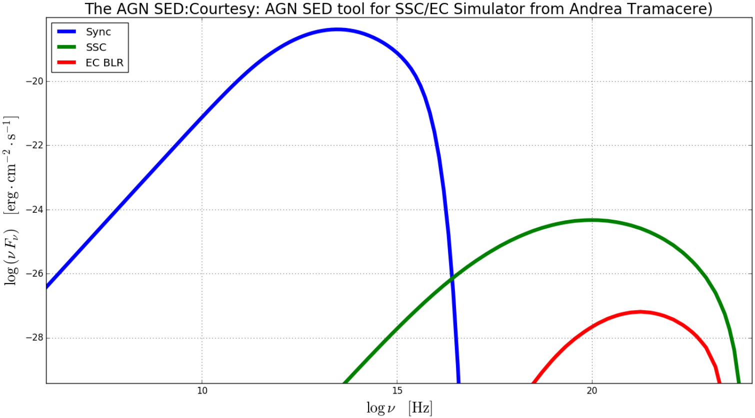


Mullti-component SED

Superposition of fluxes: External-Compton on BLR Photons

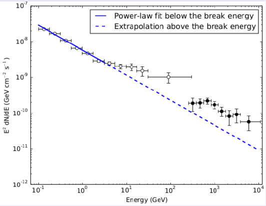
INPUT PARAMETERS

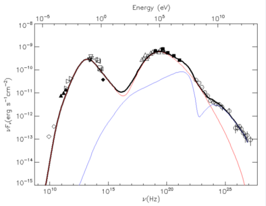
```
| Broad Line Region
| * r_in = 3e15 , r_out = 3*r_in
| * opacity in BLR = 0.1
```



The SED of Cen A

Fitting the observed data (Courtesy of H.E.S.S. and Fermi-LAT collaborations)





- Fermi-LAT and H.E.S.S.: high and very-high energy γ-rays
- contemporaneous γ-ray spectrum
- single-zone SSC model reproduces SED up to few GeV — not favourable thereafter
- additional γ-ray emitting component (two-zone SSC) required
- 2^{nd} component accounts for very-high energy data
- Question: can one-zone $\gamma\gamma$ absorption also mimic HE γ-ray tail?

Conclusion & Remarks

Ingredients

- charged particles + magnetic fields $\rightarrowtail$ synchrotron emission
- electrons (leptonic) + some target low energy photon field $\rightarrowtail$ either SSC or EC emission

$$\text{target photon fields} = \begin{cases} \hookrightarrow \text{synchrotron photons (SSC)}, \\ \hookrightarrow \text{accretion disk photons}, \\ \hookrightarrow \text{BLR photons}, \\ \hookrightarrow \text{photons from dusty torus, or} \\ \hookrightarrow \text{CMB photons} \end{cases}$$

Models for Centaurus A

- traditional one-zone leptonic models: not sufficient for Cen A HE SED
- a two-zone SSC models accounts for the HE tail of the Cen A SED
- **To do**: probe single-zone leptonic BLR $\gamma\gamma$ absorption re-production of HE γ-ray part of SED of Cen A

Special thanks to the organizers of the ACP 2018.

Artist Impression

An Active Galactic Nucleus (AGN)