γ-ray Emission of Young Radio Galaxies

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Evolution of GPS Sources: A Simple Model (I)

The evolution of GPS/CSS sources is described by the set of equations that can be derived by (i) balancing the momentum flux of a relativistic jet by the ram-pressure of the ambient medium spread over some area $A_{\rm h}$, namely $L_{\rm j}/c = \rho\, v_{\rm h}^2\, A_{\rm h}$ where $v_{\rm h}$ is the advance velocity of the jet head and $L_{\rm j}$ is the jet kinetic power; (ii) setting the lobe's sideway expansion velocity equal to the speed of the shock driven by the overpressured cocoon with internal pressure p in the surrounding medium, $v_{\rm c} = (p/\rho)^{1/2}$; and (iii) assuming that all the energy transported by a pair of jets during the source's lifetime t is transformed at the jet head (terminal shock) into the cocoon's internal pressure, $p\, V = (\hat{\gamma} - 1)\, 2\, L_{\rm j}\, t$, where V is the volume of the cocoon, and $\hat{\gamma} = 4/3$ is the adiabatic index of ultrarelativistic cocoon's fluid. Introducing the source linear size LS and its transverse size $l_{\rm c}$, one can therefore write

(1) $$L_{\rm j} = c\, \rho (LS)\, v_{\rm h}^2\, A_{\rm h} \quad , \quad p = \rho(l_{\rm c})\, v_{\rm c}^2 \quad , \quad 3\, p\, V = 2\, L_{\rm j}\, t \quad ,$$

(2) $$v_{\rm h} = \frac{d\, LS}{dt} \quad , \quad v_{\rm c} = \frac{d\, l_{\rm c}}{dt} \quad , \quad \frac{d\, V}{dt} = 2\pi\, l_{\rm c}^2\, v_{\rm h} \quad .$$

In addition to these, we introduce the scaling $l_{\rm c}^2 \propto t^{\delta}$ and fix $\delta = 1$ (see *Kawakatu & Kino 2006*). We also restrict our analysis to young GPS sources, which evolve in the central plateau of the galactic gaseous halo. Thus, we set $\rho = m_{\rm p}\, n_0$ with $n_0 \approx 0.1\,{\rm cm}^{-3}$. Finally, we assume $v_{\rm h} = 0.3\, c$ as required by observations.

Evolution of GPS Sources: A Simple Model (II)

The jet power $L_\mathrm{j} \equiv 10^{45}\, L_{\mathrm{j},\,45}$ erg s^{-1} and the source's linear size $LS \equiv 100\, LS_{100}$ pc are the two model parameters:

(3) $$p = \left(\frac{L_\mathrm{j}\, m_\mathrm{p} n_0\, v_\mathrm{h}}{6\pi}\right)^{1/2} LS^{-1} \approx 10^{-6}\, L_{\mathrm{j},\,45}^{1/2}\, LS_{100}^{-1} \quad \mathrm{erg\,cm^{-3}} \quad ,$$

(4) $$t = v_\mathrm{h}^{-1}\, LS \approx 10^{3}\, LS_{100} \quad \mathrm{yrs} \quad ,$$

(5) $$A_\mathrm{h} = \left(\frac{L_\mathrm{j}}{c\, m_\mathrm{p} n_0\, v_\mathrm{h}^2}\right) LS^{0} \approx 2.5 \times 10^{39}\, L_{\mathrm{j},\,45} \quad \mathrm{cm^2} \quad ,$$

(6) $$l_\mathrm{c} = \left(\frac{8\, L_\mathrm{j}}{3\pi\, m_\mathrm{p} n_0\, v_\mathrm{h}^3}\right)^{1/4} LS^{1/2} \approx 1.6 \times 10^{20}\, L_{\mathrm{j},\,45}^{1/4}\, LS_{100}^{1/2} \quad \mathrm{cm} \quad ,$$

(7) $$V = \left(\frac{8\pi\, L_\mathrm{j}}{3\, m_\mathrm{p} n_0\, v_\mathrm{h}^3}\right)^{1/2} LS^{2} \approx 2.5 \times 10^{61}\, L_{\mathrm{j},\,45}^{1/2}\, LS_{100}^{2} \quad \mathrm{cm^3} \quad ,$$

(8) $$v_\mathrm{c} = \left(\frac{L_\mathrm{j}\, v_\mathrm{h}}{6\pi\, m_\mathrm{p} n_0}\right)^{1/4} LS^{-1/2} \approx 2.3 \times 10^{9}\, L_{\mathrm{j},\,45}^{1/4}\, LS_{100}^{-1/2} \quad \mathrm{cm\,s^{-1}} \quad .$$

Electron Energy Distribution

We assume that the hotspots of GPS sources produce ultrarelativistic electrons at the rate and with the energy energy distribution described by some given function $Q_{\rm e}(\gamma)$. This is further (i.e. when injected into the lobes) modified by the radiative losses, to give the steady-state electron energy spectrum

(9) $$N_{\rm e}(\gamma) = \frac{1}{|\dot{\gamma}|} \int_{\gamma} Q_{\rm e}(\gamma')\, d\gamma' \quad ,$$

with the radiative cooling rate $|\dot{\gamma}| = (4\, c\, \sigma_{\rm T} / 3\, m_{\rm e} c^2)\, \gamma^2\, (U_{\rm B} + \sum_i U_{{\rm rad},\, i})$.
As for the injection rate, we assume that it may be similar to the one found for the archetype FR II radio galaxy Cygnus A *(Stawarz et al. 2007; see also a poster by Cheung et al., this conference)*. In particular, we assume

(10) $$Q_{\rm e}(\gamma) \propto \begin{cases} \gamma^{-s_1} & \text{for} \quad \gamma < \gamma_{\rm int} \approx m_{\rm p}/m_{\rm e} \\ \gamma_{\rm int}^{s_2 - s_1}\, \gamma^{-s_2} & \text{for} \quad \gamma_{\rm int} < \gamma < 100\, \gamma_{\rm int} \end{cases}$$

with $s_1 \sim 1.5$ and $s_2 \gtrsim 3$. Such an injection form is in fact expected in the case of cold protons carrying bulk of the jet energy, due to the very nature of the particle acceleration process taking place at the terminal (mildly relativistic) shocks dynamically dominated by p^+.

Synchrotron Emission

For a given electron energy distrbution $N_{\rm e}(\gamma)$, the monochromatic synchrotron luminosity is

(11)
$$[\nu L_\nu]_{\rm syn} = \frac{2}{3} c\,\sigma_T\,V\,U_{\rm B}\,\left[\gamma^3\,N_{\rm e}(\gamma)\right]_{\gamma=\sqrt{4\,\pi\,m_{\rm e} c\,\nu/3\,e\,B}} \quad .$$

Here we take the magnetic field energy density $U_{\rm B} = \eta_{\rm B}\,p$ with $\eta_{\rm B} \lesssim 3$, and hence the lobes' magnetic field intensity

(12)
$$B = (8\pi\,\eta_{\rm B}\,p)^{1/2} \approx 5\,\eta_{\rm B}^{1/2}\,L_{\rm j,\,45}^{1/4}\,LS_{100}^{-1/2} \quad {\rm mG} \quad .$$

The synchrotron emission is further modified by the absorption effects. Here we adopt and modify the model proposed by *Begelman (1999)*, in which dense hydrogen clouds of ISM engulfed by the expanding lobe are photoionized by the active nucleus (i.e., by the UV emission of the accretion disk), causing free-free absorption of radio photons. We identify the clouds with the ones present at pc$-$kpc distances from the center, producing narrow-line emission. In particular, our model requires that only a few percent of the NLR clouds — which are characterized by the total mass $M_{\rm NLR} \sim 10^7\,M_\odot$, filling factors $\phi \sim 10^{-4}$, and the number density decreasing with the distance from the ceneter $n_{\rm NLR} \propto r^{-n}$ with $1 < n < 2$, as observed in nearby Seyfert galaxies — is engulfed by the expanding lobes.

Inverse-Compton Emission

For a given electron energy distrbution $N_{\rm e}(\gamma)$, the SSC and IC luminosities related to the external photon fields can be evaluated as, respectively,

(13) $$[\nu L_\nu]_{\rm ssc} \approx \frac{2}{3}\,\sigma_{\rm T}\,\frac{l_{\rm c}}{3}\int_{3\nu/4\gamma_{\rm max}^2}^{3\nu/4\gamma_{\rm min}^2} L_{\nu_0,\,{\rm syn}}\,\left[\gamma^3\,N_{\rm e}(\gamma)\right]_{\gamma=\sqrt{3\nu/4\nu_0}}\,d\nu_0 \quad , \quad \text{and}$$

(14) $$[\nu L_\nu]_{\rm IC/rad} = \frac{2}{3} c\,\sigma_T\,V\,U_{\rm rad}\,\left[\gamma^3\,N_{\rm e}(\gamma)\right]_{\gamma=\sqrt{3\nu/4\nu_0}} \quad .$$

The energy densities of different photon fields within the lobes of GPS sources are: (i) the UV emission of the accretion disk averaged over the lobes' volume

(15) $$U_{\rm UV} = \frac{1}{V}\int \frac{L_{\rm UV}}{4\pi\,LS^2\,c}dV \approx 10^{-6}\,L_{\rm UV,\,46}\,LS_{100}^{-2} \quad {\rm erg\,cm^{-3}}$$

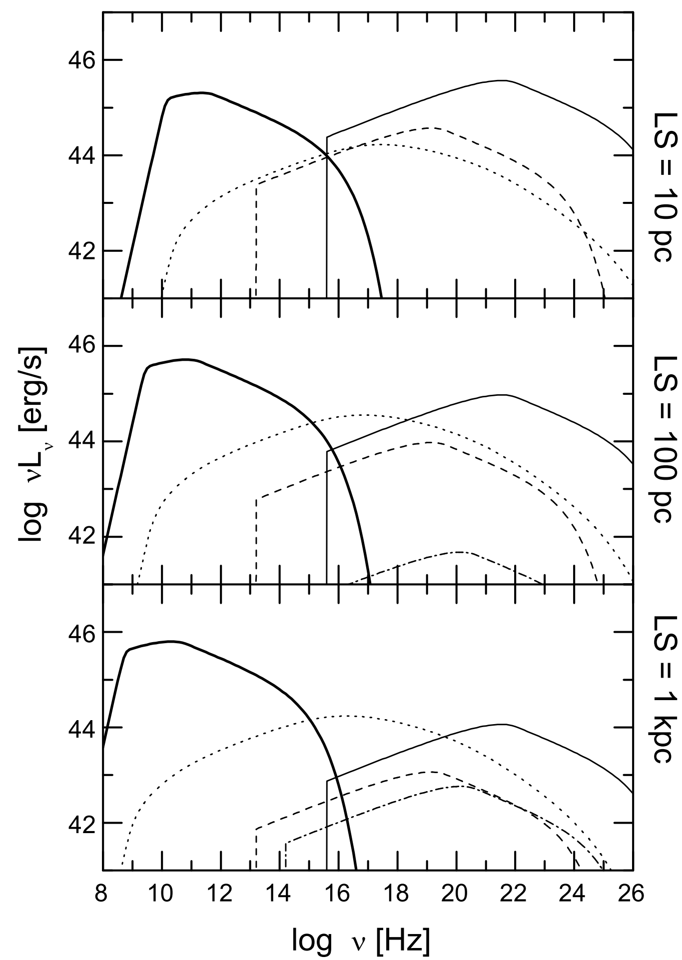
where $L_{\rm UV,\,46} \equiv L_{\rm UV}/10^{46}$ erg s^{-1}; (ii) the analogous FIR emission of the dusty torus $U_{\rm IR} \approx 0.1\,U_{\rm UV} \approx 10^{-7}\,L_{\rm UV,\,46}\,LS_{100}^{-2}$ erg cm^{-3}; (iii) the synchrotron emission of radio lobes $U_{\rm syn} = \int L_{\nu,\,{\rm syn}}\,d\nu/(4\pi\,l_{\rm c}\,LS\,c)$; (iv) the starlight emission, $U_{\rm star} = 3\,L_{\rm V}/(4\pi\,r_{\rm s}^2\,c) \approx 8\times10^{-10}\,L_{\rm V,\,45}^{-1}$ erg cm^{-3}, where the V-band luminosity of the host galaxy is $L_{\rm V,\,45} \equiv L_{\rm V}/10^{45}$ erg s^{-1}.

Broad-Band Spectra (I)

Broad-band spectra of non-thermal emission produced within lobes of GPS radio galaxies with different linear sizes LS, different jet power $L_{\rm j}$, and fixed parameters $L_{\rm UV,\,46} = 1$, $L_{\rm V,\,45} = 1$, $s_1 = 1.5$, $s_2 = 2.5$. Energy equipartition between the lobes' electrons, protons and magnetic field was assumed. In th enext figures

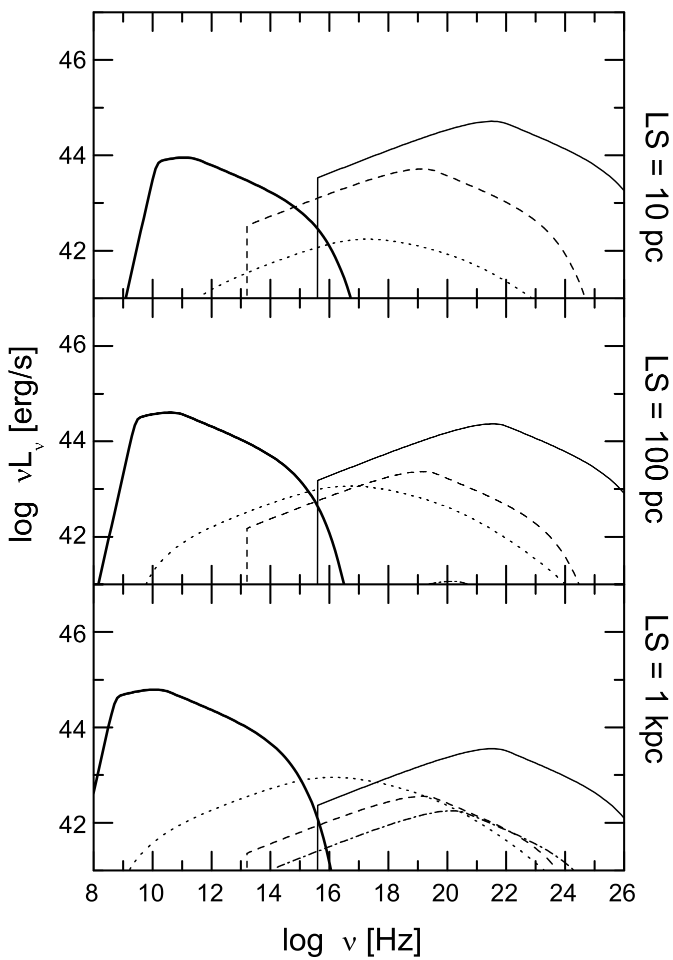
- solid thick lines: synchrotron,
- dotted lines: SSC,
- dashed lines: IC/IR,
- dot-dashed lines: IC/star
- thin solid lines: IC/UV.

$L_{\rm j} = 10^{47}$ erg s^{-1}

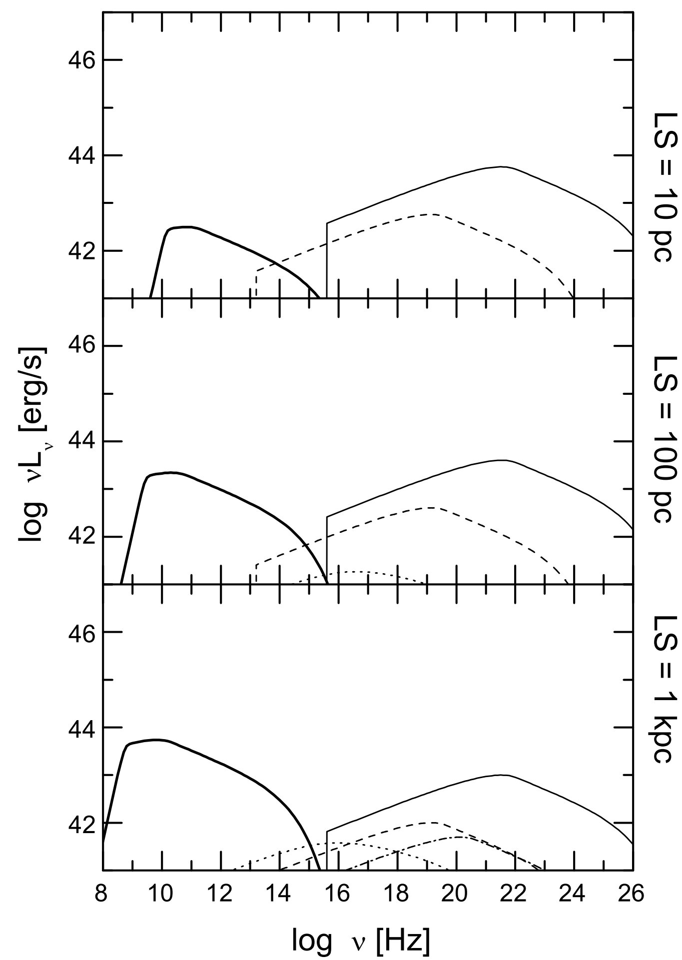


Broad-Band Spectra (II)

$L_{\rm j} = 10^{46}\,\mathsf{erg\,s}^{-1}$



$L_{\rm j} = 10^{45}\,\mathsf{erg\,s}^{-1}$



Conclusions

- Complex synchrotron continua of GPS radio galaxies with break/critical frequencies arising due to the absorption process, the intrinsic curvature of the electron energy distribution, and the cooling effects.
- Relatively strong non-thermal X-ray emission of GPS radio galaxies due to the IC radiation of radio lobes;
- Strong γ-ray emission due to the IC upscattering of UV photons from the accretion disk within radio lobes of compact GPS radio galaxies (detectable by *GLAST*!).