What the synchrotron cut-off can tell us about magnetic turbulence in the hotspots of radiogalaxies

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Cosmic Rays Origin - beyond the standar model
San Vito di Cadore - September 18-24, 2016

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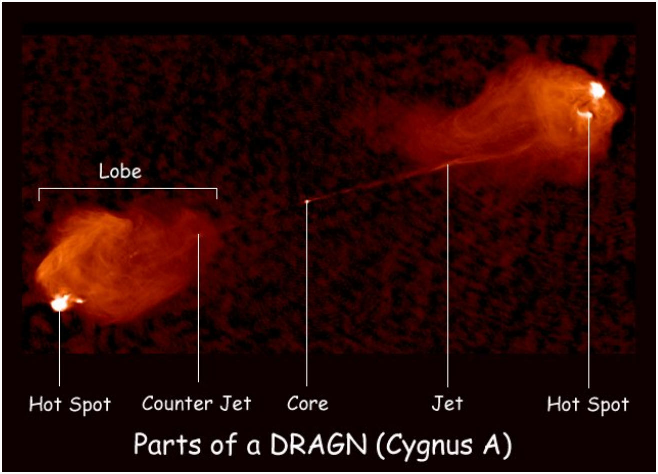
Introduction

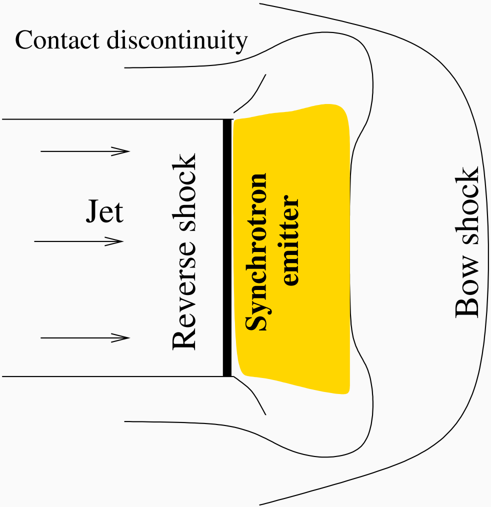
Hotspots in radiogalaxies

Bright (synchrotron) radio knots of $\sim$1 kpc embedded in larger lobes of shocked plasma



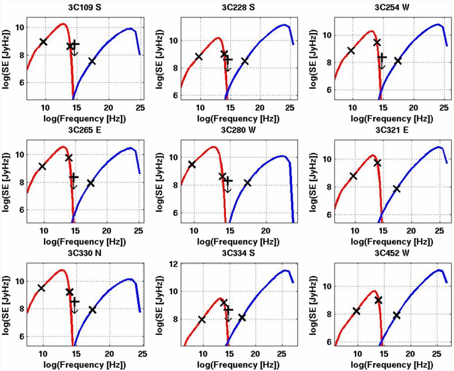
Jet termination shocks

Electrons accelerated in the reverse shock emit synchrotron radiation



Multiwavelength (leptonic) emission

- **Radio-to-optical:** synchrotron
- **X-rays:** Compton upscattering of CMB/synchrotron photons

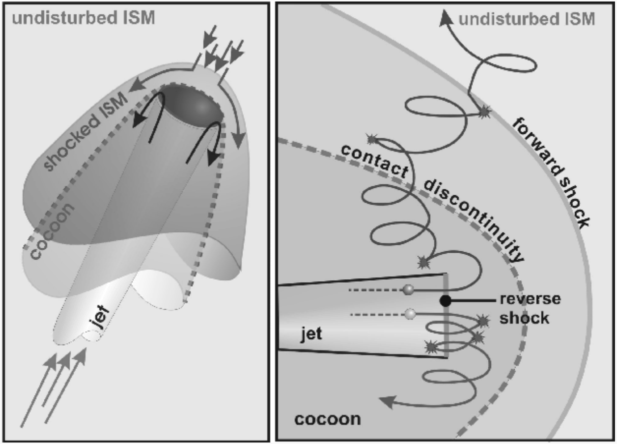


Werner et al. (2012)

$$E_{e,\max} \sim 0.2 \left(\frac{\nu_c}{10^{14}\,\mathrm{Hz}}\right)^{0.5} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-0.5} \mathrm{TeV} \ll E_{\mathrm{UHECR}}$$

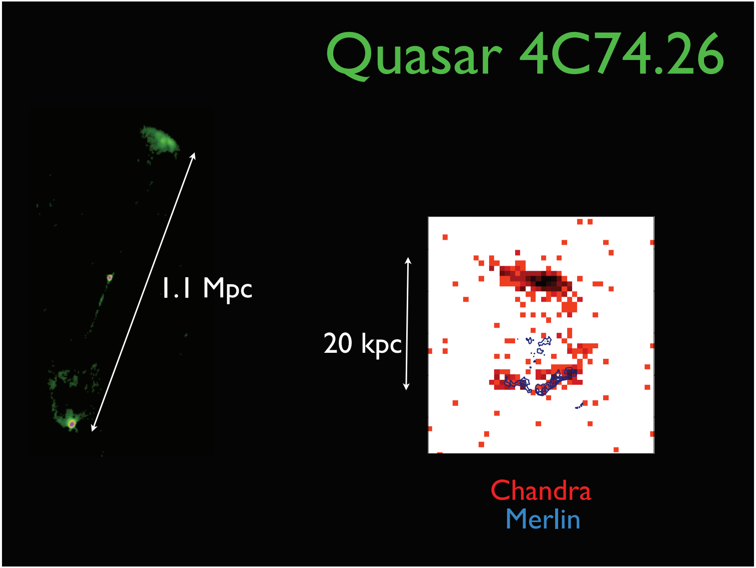
Reigning paradigm

- $E_{e,\max}$ is determined by synchrotron losses ($t_{\rm acc} = t_{\rm synchr}$)
- Hadronic losses are minimal; protons are accelerated up to very high energies and escape



Heinz & Sunyaev (2002)

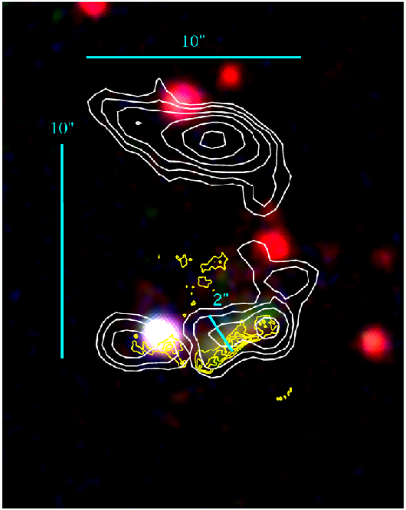
Magnetic field amplification.
The case study 4C 74.26



$z \sim 0.104$ ($1'' \sim 1.8$ kpc) | $d \sim 400$ Mpc

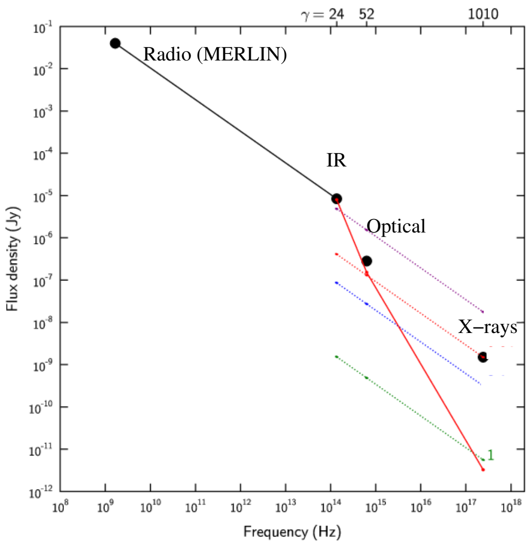
Multi-wavelength data

- Radio (MERLIN): yellow contours
- IR (Gemini): red + green
- Optical (WHT): blue
- X-rays (Chandra): white contours



Erlund et al. (2010)

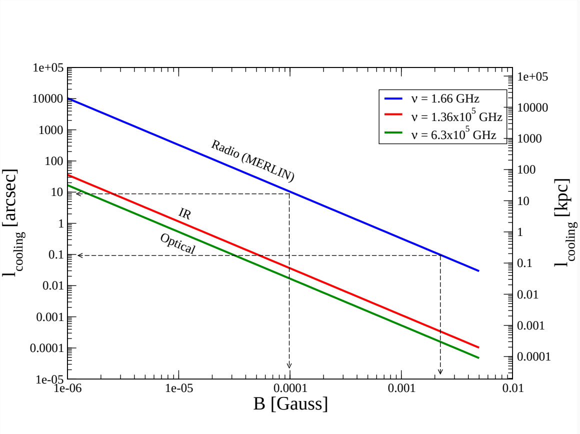
Radio-to-IR spectral index: $\alpha = 0.75$ $(p = 2.5)$



Adapted from Erlund et al. (2010)

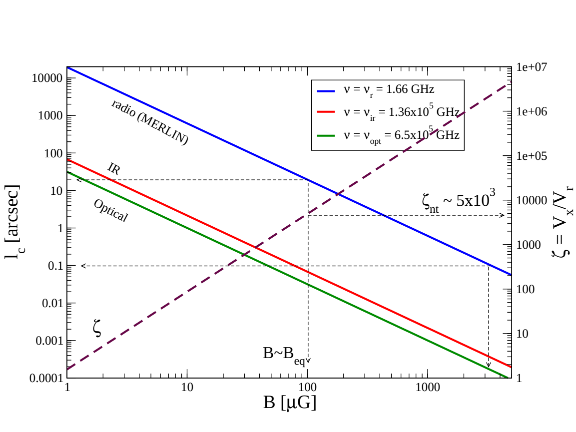
Radio-to-optical: synchrotron

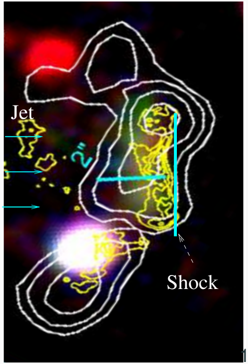
- Emitting electrons $\gamma \sim 5 \times 10^3 \left(\frac{\nu}{\mathrm{GHz}}\right)^{0.5} \left(\frac{B}{100\mu\mathrm{G}}\right)^{-0.5}$
- Cooling length $l_{\mathrm{cooling}} \sim 12'' \left(\frac{\nu}{\mathrm{GHz}}\right)^{-0.5} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-1.5} \left(\frac{v_{\mathrm{sh}}}{c/3}\right)$



X-rays: Upscattering of CMB photons (IC)

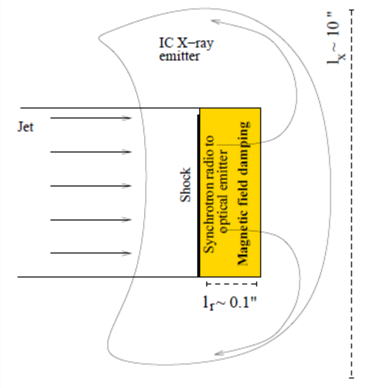
- Cooling length: $l_{\rm ic}(\gamma_{\rm x}) \sim 10^4 \left(\frac{v_{\rm sh}}{c/3}\right)$ arcsec $\gg 10''$
- Adiabatic expansion is the dominant cooling mechanism as the particles flow out of the hotspot
- $\frac{f_x}{f_{1.66}} \Rightarrow \zeta \equiv \frac{V_x}{V_{1.66}} \sim 5 \times 10^3 \left(\frac{B}{100\mu{\rm G}}\right)^{1.75}$





4C 74.26 hotspot as a magnetic damping region

- Thin synchrotron (radio) emitter: slow synchrotron cooling
- Larger X-ray emission region: determined by advection



MERLIN emitter traces out the region where the magnetic field is amplified (and it's damped at ~ 0.1 kpc downstream of the shock)

Revising the reigning paradigm

Mean-free path upper-limit

$$\frac{E_{e,\max}}{\mathrm{TeV}} \sim 0.2 \left(\frac{\nu_{\rm c}}{10^{14}\,\mathrm{Hz}}\right)^{\frac{1}{2}} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-\frac{1}{2}}$$

Larmor radius:

$$\frac{r_{\rm g}(E_{e,\max})}{\mathrm{cm}} \sim 10^{13} \left(\frac{\nu_{\rm c}}{10^{14}\,\mathrm{Hz}}\right)^{0.5} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-1.5}$$

Table 5. Physical parameters.

Source	$\nu_{\rm b}$ (GHz)	α	$B_{\rm eq}$ (μG)	$t_{\rm rad}$ (10^3 yr)	Distance (kpc)
3C 105S	1.37×10^5	0.75	75	6.4	278
3C 195N	$<2.7 \times 10^5$	0.95	62	> 6.0	117
3C 195S	5.34×10^5	1.00	78	3.0	127
3C 227WE	3.0×10^5	0.65	126	2.0	173
3C 227E	1.14×10^6	0.75	99	1.5	169
3C 403W	$<2.95 \times 10^4$	0.55	38	>39	52
3C 445N	6.63×10^5	0.85	60	4.1	315
3C 445S	8.40×10^5	0.80	68	2.8	275

Mack et al. (2009)

Accelerated particles interacting with magnetic turbulence of random scale size s ($\ll r_{\rm g}$) are deflected by an angle $\theta \sim s/r_{\rm g}$

- Mean free path $\lambda = \frac{r_{\rm g}}{\theta} \sim \frac{r_{\rm g}^2}{s}$
- Ion skin-depth: $\frac{c}{\omega_{\rm pi}} \sim 10^9 \left(\frac{n_{\rm j}}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{-\frac{1}{2}}$ cm

$$s \geq c/\omega_{\rm pi}$$

$$\lambda_{\max} \equiv \frac{r_{\rm g}^2(E_{e,\max})}{c/\omega_{\rm pi}} \sim 0.02 \left(\frac{\nu_{\rm c}}{10^{14}\,\mathrm{Hz}}\right) \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-3} \left(\frac{n_{\rm j}}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{0.5} \mathrm{pc}$$

Diffusion coefficient upper-limit

$E_{e,\mathrm{max}} \sim 0.2 \left(\frac{\nu_\mathrm{c}}{10^{14}\,\mathrm{Hz}}\right)^{\frac{1}{2}} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-\frac{1}{2}}$ TeV

Larmor radius: $r_\mathrm{g}(E_{e,\mathrm{max}}) \sim 10^{13} \left(\frac{\nu_\mathrm{c}}{10^{14}\,\mathrm{Hz}}\right)^{0.5} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-1.5}$ cm

$$\boxed{\lambda_\mathrm{max} \equiv \frac{r_\mathrm{g}^2(E_{e,\mathrm{max}})}{c/\omega_\mathrm{pi}} \sim 0.02 \left(\frac{\nu_\mathrm{c}}{10^{14}\,\mathrm{Hz}}\right) \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-3} \left(\frac{n_\mathrm{j}}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{0.5} \mathrm{pc}}$$

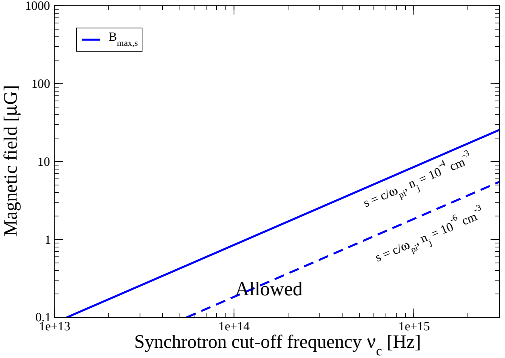
$$\boxed{\frac{D_\mathrm{max}}{D_\mathrm{Bohm}} \sim \frac{r_\mathrm{g}(E_{e,\mathrm{max}})}{c/\omega_\mathrm{pi}} \sim 3 \times 10^4 \left(\frac{\nu_\mathrm{c}}{10^{14}\,\mathrm{Hz}}\right)^{0.5} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-1.5} \left(\frac{n_\mathrm{j}}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{0.5}}$$

Reigning paradigm

Synchrotron losses determine $E_{e,\max}$

$$t_{\rm synchr} = t_{\rm acc} \Rightarrow \lambda_{\rm synchr} \sim 25 \left(\frac{v_{\rm sh}}{c/3}\right)^2 \left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)^{-1/2} \left(\frac{B}{100\,\mu{\rm G}}\right)^{-3/2} \;{\rm pc}$$

$$\boxed{\lambda_{\rm synchr} \leq \lambda_{\max} \Rightarrow B \leq B_{\rm max,s} = 0.5 \left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right) \left(\frac{v_{\rm sh}}{c/3}\right)^{-\frac{1}{3}} \left(\frac{n_{\rm j}}{10^{-4}{\rm cm}^{-3}}\right)^{\frac{1}{3}} \;\mu{\rm G}}$$



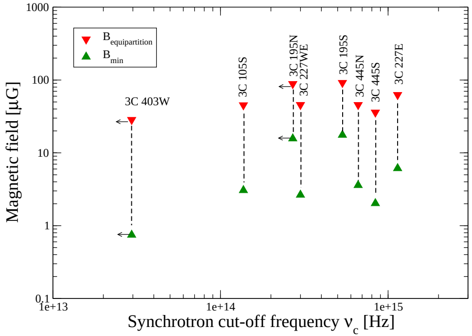
Synchrotron flux at 8.4 GHz

- Equipartition field: $(1+a)U_e = U_{\rm mag}$

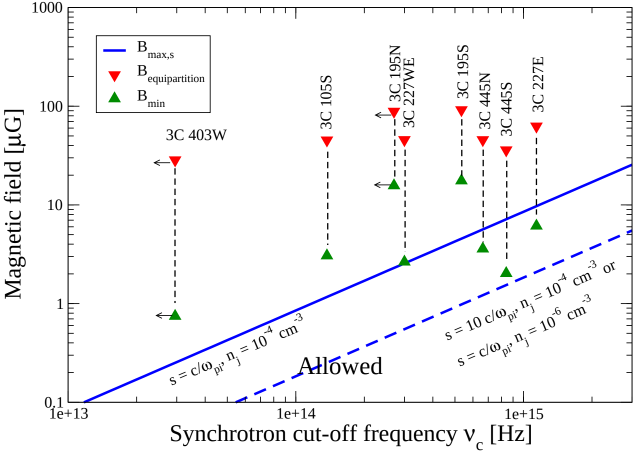
$$\frac{B_{\rm eq}}{\mu{\rm G}} \sim 220\,(1+a)^{0.27}\left(\frac{\gamma_{\rm min}}{100}\right)^{-0.28}\left(\frac{L_{8.4}}{10^{40}\,{\rm erg\,s^{-1}}}\right)^{0.27}\left(\frac{V_{8.4}}{\rm kpc^3}\right)^{-0.27}$$

- Minimum field: $U_e \sim U_{\rm kin}$

$$\frac{B_{\rm min}}{\mu{\rm G}} \sim 27\left(\frac{\gamma_{\rm min}}{100}\right)^{-0.28}\left(\frac{L_{8.4}}{10^{40}\,{\rm erg\,s^{-1}}}\right)^{0.57}\left[\left(\frac{V_{8.4}}{\rm kpc^3}\right)\left(\frac{n_{\rm j}}{10^{-4}{\rm cm^{-3}}}\right)\right]^{-0.57}$$



Observations + plasma physics



Araudo et al. (2016)

Therefore, synchrotron losses don’t constrain the maximum energy of electrons accelerated in the termination shocks of powerful AGN jets

What’s the mechanism that stop particle acceleration in AGN jets termination shocks?

Fermi acceleration in perpendicular shocks

Magnetic field amplification: $B \gg B_{\rm j}$ is required to explain synchrotron radio fluxes ($B_{\rm hs} \sim B + 4B_{\rm j} \sim B$)

Condition for particle acceleration: $\lambda(B) \leq r_{\rm g}(4B_{\rm j})$ [1]

$$\lambda(E_{e,\rm max}, B) = r_{\rm g}(E_{e,\rm max}, 4B_{\rm j}) \Rightarrow s = r_{\rm g}(E_{e,\rm max}, B)\left(\frac{4B_{\rm j}}{B}\right)$$

$$\boxed{s \sim 5\times 10^{11}\left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)^{\frac{1}{2}}\left(\frac{B_{\rm j}}{\mu{\rm G}}\right)\left(\frac{B}{100\mu{\rm G}}\right)^{-\frac{5}{2}}\ {\rm cm} \sim 500\frac{c}{\omega_{\rm pi}}}$$

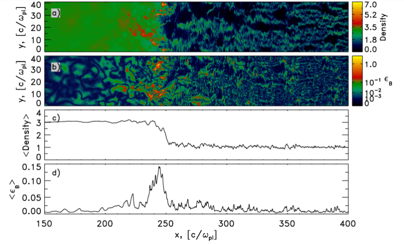
$$\boxed{\frac{D}{D_{\rm Bohm}} \sim \frac{r_{\rm g}(E_{e,\rm max})}{s} \sim 20\left(\frac{B}{100\,\mu{\rm G}}\right)\left(\frac{B_{\rm j}}{\mu{\rm G}}\right)^{-1}}$$

[1] $\lambda(B) > r_{\rm g}(4B_{\rm j}) \Rightarrow$ particles follow $4B_{\rm j}$-helical orbits and diffusion is ceased (Lemoine & Pelletier, 2010, Sironi et al. 2013, Reville & Bell, 2014)

Plasma instabilities in astrophysical shocks

Weibel instabilities

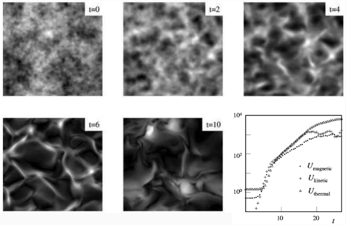
- $s \sim \frac{c}{\omega_{pi}}$
- Quick decay of small scale turbulence ($l_{\mathrm{damp}} \sim 100\frac{c}{\omega_{pi}}$)



Spitkovsky (2008)

Non resonant hybrid (NRH) instabilities

- $s \sim r_{\mathrm{g}}$
- Synchrotron X-ray filaments in supernova remnants



Bell (2004), Bell (2005)

NRH instabilities in mildly relativistic shocks

- Maximum energy of CRs driving the instability

$$E_{\rm s} = E_{e,\max}\left(\frac{B_{\rm jd}}{B}\right) \sim 10\left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)^{\frac{1}{2}}\left(\frac{B_{\rm j}}{\mu{\rm G}}\right)\left(\frac{B}{100\mu{\rm G}}\right)^{-\frac{5}{2}}\ {\rm GeV}$$

- Condition for efficient magnetic field amplification by the NRH instabilities

$$\eta \gtrsim 0.04\left(\frac{B_{\rm j}}{\mu{\rm G}}\right)\left(\frac{\Gamma_{\rm j}-1}{0.06}\right)^{-\frac{1}{2}}\left(\frac{n_{\rm j}}{10^{-4}\,{\rm cm}^{-3}}\right)^{-\frac{1}{2}}$$

Final remarks

Conclusions

- The thin (MERLIN) radio emitter in the hotspot of 4C74.26 traces out the region where **the magnetic field is amplified**
- Based on one observable ($\nu_{\rm c}$) and one physical constraint ($s \geq c/\omega_{\rm pi}$), we found that $E_{e,\max}$ **cannot be determined by synchrotron losses**, as usually assumed
- We propose that $E_{e,\max}$ **is constrained by the streaming of low-energy cosmic rays** ($s \sim 500\, c/\omega_{\rm pi}$)
- Given that ion radiation losses are minimal, **the same limit applies to protons**

This may have important implications for the understanding of the origins of UHECR

Extra slides

Synchrotron flux at 8.4 GHz

Electrons energy density

$$\frac{U_e}{\mathrm{erg\,cm^{-3}}} \sim$$

$$10^{-9}\left(\frac{p-2}{0.5}\right)^{-1}\left(\frac{\gamma_{\rm min}}{100}\right)^{2-p}\left(\frac{\nu}{8.4\,\mathrm{GHz}}\right)^{\frac{p-3}{2}}\left(\frac{L_{8.4}}{10^{41}\ \mathrm{erg\,s^{-1}}}\right)\left(\frac{V}{\mathrm{kpc}^3}\right)^{-1}\left(\frac{B}{100\mu\mathrm{G}}\right)^{\frac{-p-1}{2}}$$

Equipartition field:

$$\frac{B_{\rm eq}}{\mu\mathrm{G}} \sim$$

$$220^{\frac{7.5}{p+5}}\left[(1+a)\left(\frac{p-2}{0.5}\right)^{-1}\left(\frac{\gamma_{\rm min}}{100}\right)^{2-p}\left(\frac{\nu}{8.4\,\mathrm{GHz}}\right)^{\frac{p-3}{2}}\left(\frac{L_{8.4}}{10^{41}\ \mathrm{erg\,s^{-1}}}\right)\left(\frac{V}{\mathrm{kpc}^3}\right)^{-1}\right]^{\frac{2}{p+5}}$$

Minimum field:

$$\frac{B_{\rm min}}{\mu\mathrm{G}} \sim$$

$$27^{\frac{3.5}{p+1}}\left(\frac{\gamma_{\rm min}}{100}\right)^{\frac{4-2p}{(p+1)}}\left(\frac{\nu}{8.4\,\mathrm{GHz}}\right)^{\frac{p-3}{p+1}}\left(\frac{L_{8.4}}{10^{41}\ \mathrm{erg\,s^{-1}}}\right)^{\frac{2}{p+1}}\left[\left(\frac{\Gamma_{\rm j}-1}{0.06}\right)\left(\frac{p-2}{0.5}\right)\left(\frac{V}{\mathrm{kpc}^3}\right)\left(\frac{n_{\rm j}}{10^{-4}\mathrm{cm}^{-3}}\right)$$

Plasma physics

- We consider the jet as a hydrogen plasma with electron and proton thermal Lorentz factors $\bar{\gamma}_e$ and $\bar{\gamma}_p \sim \Gamma_{\rm j}$, respectively

- Ion skin-depth: $\frac{c}{\omega_{\rm pi}} \sim 10^9 \sqrt{\Gamma_{\rm j}} \left(\frac{n_{\rm j}}{10^{-4}\ {\rm cm}^{-3}}\right)^{-\frac{1}{2}}\ {\rm cm}$

- The thermal electron Larmor radius is generally larger than $c/\omega_{\rm pi}$ (in the "hot electrons/cold protons" scenario):
$\frac{r_{\rm g}(\bar{\gamma}_e)}{c/\omega_{\rm pi}} =\sim 2 \frac{\bar{\gamma}_e}{\Gamma_{\rm j}} \left(\frac{\sigma_{\rm j}}{10^{-6}}\right)^{-\frac{1}{2}}$

  $\sigma_{\rm j} \equiv \frac{U_{\rm mag,j}}{U_{\rm kin}} \sim 4 \times 10^{-6} \left(\frac{B_{\rm j}}{\mu{\rm G}}\right)^2 \left(\frac{\Gamma_{\rm j}-1}{0.06}\right)^{-1} \left(\frac{n_{\rm j}}{10^{-4}\ {\rm cm}^{-3}}\right)^{-1}$

Therefore, $c/\omega_{\rm pi}$ is the smallest characteristic plasma scalelength

Constraints on the maximum energy

$$E_{e,\max} \sim 0.2 \left(\frac{\nu_c}{10^{14}\,\mathrm{Hz}}\right)^{\frac{1}{2}} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-\frac{1}{2}} \;\mathrm{TeV}$$

× Hillas condition (Larmor radius = size of the system):
$\frac{r_g}{\mathrm{cm}} \sim 10^{13} \left(\frac{\nu_c}{10^{14}\,\mathrm{Hz}}\right)^{1/2} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-1/2} \ll L$

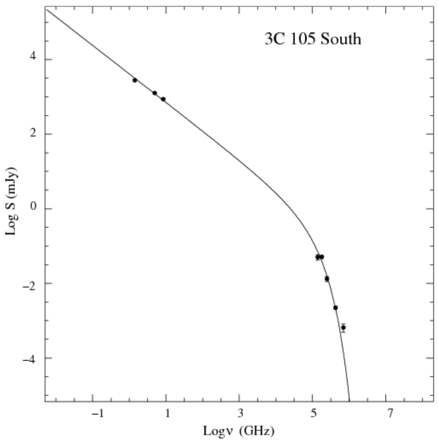
× Radiative losses: $t_{\mathrm{acc}} = t_{\mathrm{synchr}}$:
$\frac{\lambda}{\mathrm{pc}} \sim 25 \left(\frac{v_{\mathrm{sh}}}{c/3}\right)^{2} \left(\frac{\nu_c}{10^{14}\,\mathrm{Hz}}\right)^{-1/2} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-3/2} \mathrm{pc} > \lambda_{\max}$

? Structure of the magnetic field $\lambda(B) \leq r_g(B_j)$

Maximum energy of relativistic electrons

Turnover of the synchrotron spectrum: $\nu_c = 10^{14} - 10^{15}$ Hz

$$E_{e,\max} \sim 0.2 \left(\frac{\nu_c}{10^{14}\,\mathrm{Hz}}\right)^{0.5} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-0.5} \quad \mathrm{TeV} \ll E_{\mathrm{UHECR}}$$



Sources of Ultra High Energy Cosmic Rays

Larmor radius ($r_{\rm g} = \frac{E}{ZqB}$) = size of the source ($L$)

$$\left(\frac{B}{10^{-4}\,\mathrm{G}}\right) = \frac{1}{Z}\left(\frac{E}{100\,\mathrm{EeV}}\right)\left(\frac{L}{\mathrm{kpc}}\right)^{-1}$$