Particle acceleration at jet termination shocks

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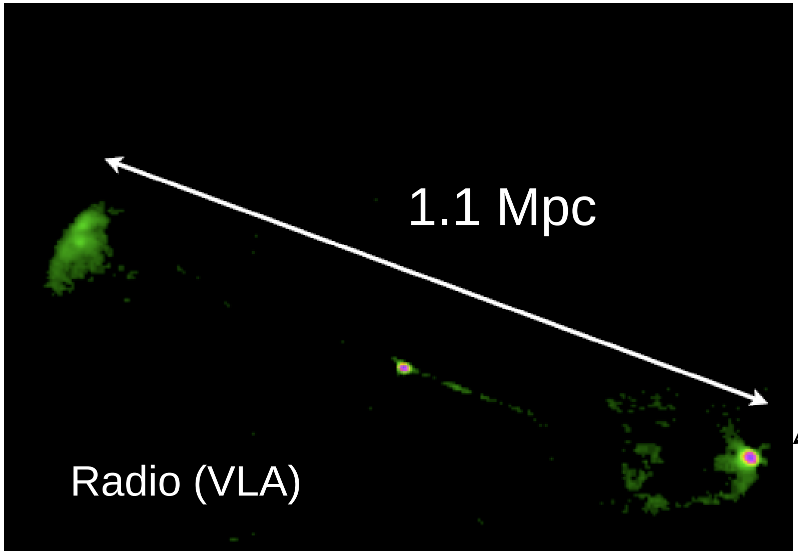
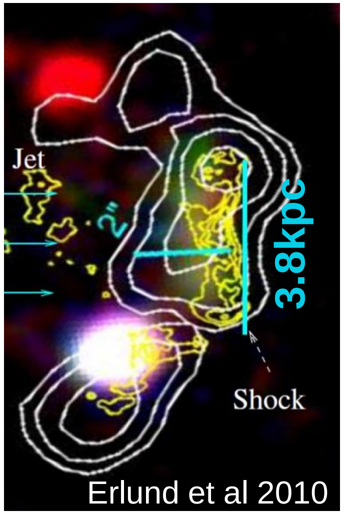
Image Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Radio: NSF/NRAO/AUI/VLA

Quasar jet 4C74.26





x-rays, radio, infrared, optical

Quasar jet 4C74.26

Araudo, Bell, Blundell ApJ (2015)

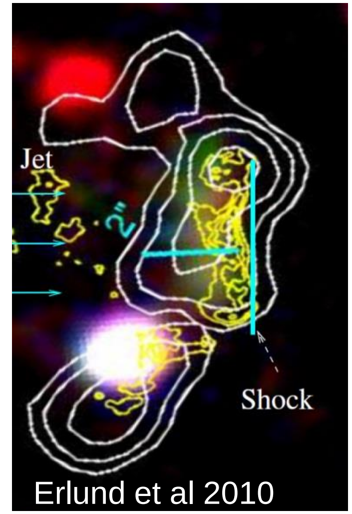
White contours: (x-ray)

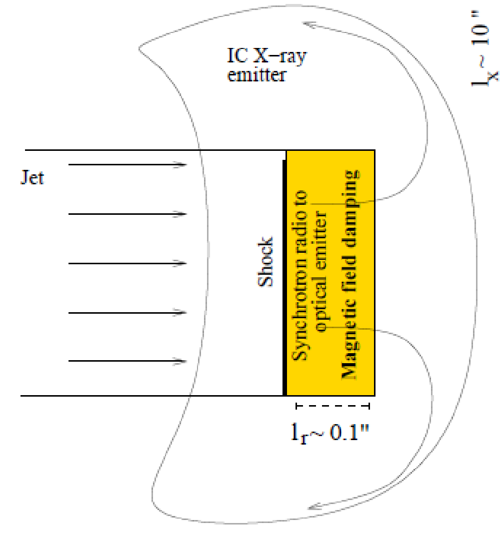
inverse Compton (on CMB) from GeV electrons

Yellow contours (1.66GHz Merlin):

synchrotron from GeV electrons

Red/green: infrared/optical synchrotron



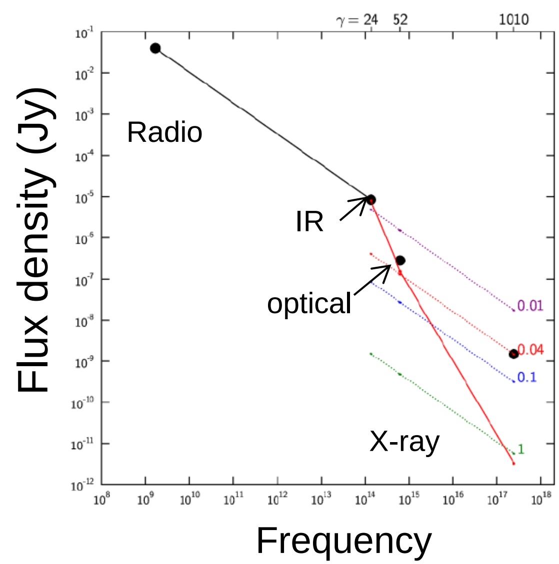


Radio too thin for electron radiative cooling

Magnetic field decays rapidly – but slower than Weibel decay

Turnover in IR/optical: electron energy = 100's GeV

$D \sim 10^6 D_{Bohm}$ if acceleration rate = synchrotron loss rate



Similar low E_{max} in other hotspots (Mack et al 2009)

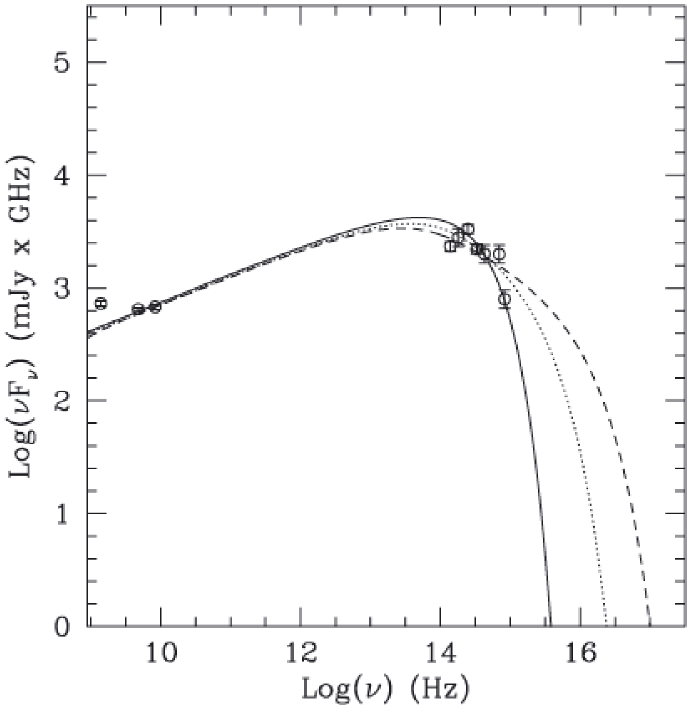


Table 5. Physical parameters.

Source	ν_b (GHz)	α	B_{eq} (μG)	t_{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

Max electron energy (optical turnover, B=100μG)

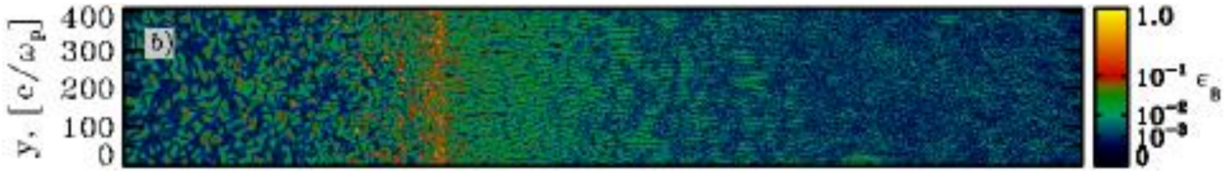
$$E_{\mathrm{max}} \sim 400\mathrm{GeV}$$

Why is E_{max} so low?

For details see: Araudo et al MNRAS (2016)

Scattering by small scale structure (as in Weibel)

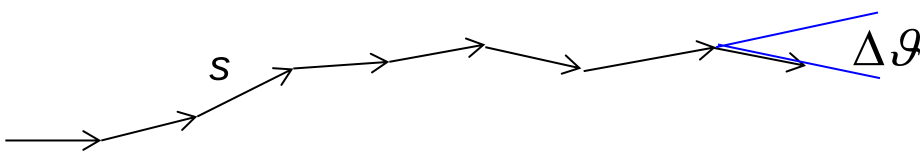
Spitkovsky 2008



or as in presentation by Laurent Gremillet yesterday

Imagine turbulence consisting of random cells of size s $\quad (s << r_g)$

Larmor radius



Each cell deflects through angle $\Delta\vartheta \approx \dfrac{s}{r_g}$

Mean free path $\lambda \approx \dfrac{s}{\Delta\vartheta^2} \approx \dfrac{r_g^{\,2}}{s}$

Diffusion coefficient $\dfrac{D}{D_{Bohm}} \approx \dfrac{r_g}{s}$

OPTION 1: Hillas limit (1985) E_{max} = uBR

Hillas limit assumes $D \sim D_{\mathrm{Bohm}}$ (CR mean free path ~ CR Larmor radius)

Generalised for non-Bohm diffusion (Lagage & Cesarsky 1983)

$$E_{\max} = \left(\frac{R}{\mathrm{kpc}}\right)\left(\frac{B_0}{\mu\mathrm{G}}\right)\left(\frac{D}{D_{Bohm}}\right)^{-1} \mathrm{EeV}$$

In non-linear turbulence expect $D_{protons} \sim D_{electrons}$

For B=100μG, R=3kpc, E_{max} =400GeV

$D \sim 10^9 D_{Bohm}$ **Implies inconceivably long CR mean free path**

Requires $s \sim 10^{-4} c / \omega_{pi}$ (Impossible)

OPTION 2: Synchrotron cooling

Turbulence even on scale s=c/ω_{pi} not reproduce $D/D_{bohm} \sim 10^6$

Mean free path in random magnetic field B on scale c/ω_{pi}

$$\boxed{\lambda_{\max} = \frac{r_g^2(\gamma_c)}{c/\omega_{pi}}} \sim 0.02 \left(\frac{\nu_c}{10^{14}\,\mathrm{Hz}}\right) \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-3} \left[\left(\frac{r}{7}\right)\left(\frac{n_j}{10^{-4}\,\mathrm{cm}^{-3}}\right)\right]^{\frac{1}{2}} \mathrm{pc},$$

Corresponding diffusion coefficient relative to Bohm

$$\frac{\mathcal{D}_{\max}}{\mathcal{D}_{\mathrm{Bohm}}} = \frac{\lambda_{\max}}{r_g(\gamma_c)} = \boxed{3.2 \times 10^4} \left(\frac{\nu_c}{10^{14}\,\mathrm{Hz}}\right)^{\frac{1}{2}} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-\frac{3}{2}} \left[\left(\frac{r}{7}\right)\left(\frac{n_j}{10^{-4}\,\mathrm{cm}^{-3}}\right)\right]^{\frac{1}{2}}.$$

Synchrotron cooling cannot explain turnover;   requires $D \sim 10^6$–$10^7\, D_{\mathrm{Bohm}}$

Acceleration rate has to be inconceivably slow to lose out to radiation losses

Any other limit to max electron energy also affects ions

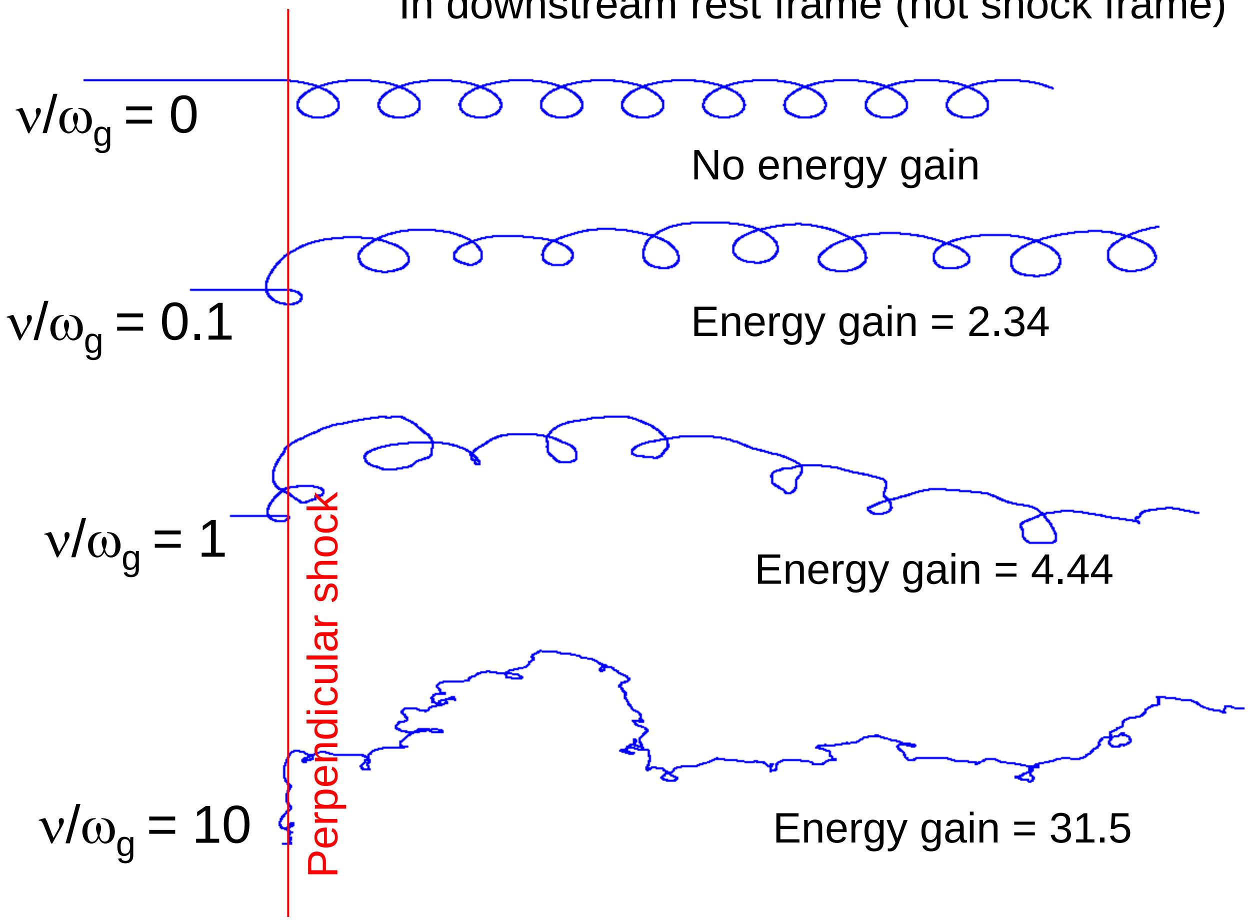
Therefore

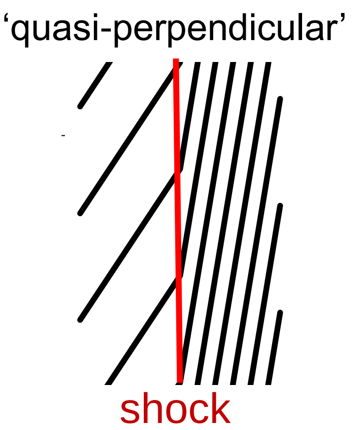
Proton acceleration is also limited to ~ 400 GeV

Option 3: Perpendicular shocks

Previous discussions:
Lemoine & Pelettier (2010), Sironi, Spitkovsky & Arons (2013), Reville & Bell (2014)

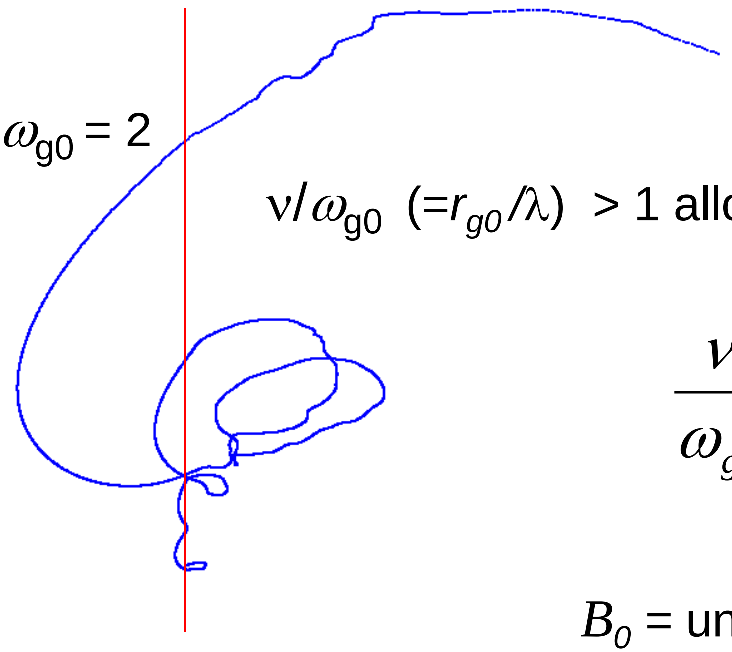
Monte Carlo with fixed scattering downstream, no scattering upstream
In downstream rest frame (not shock frame)





Need $\nu/\omega_g > 1$ ($\lambda < r_g$) for reasonable energy gain

Option 3 continued: acceleration when $\nu/\omega_{g0} > 1$, $s \ll r_g$



ν/ω_{g0} $(=r_{g0}/\lambda)$ > 1 allows particle to return from downstream

$$\frac{\nu}{\omega_{g0}} = \frac{scB_{amp}^2}{E(eV)B_0}$$

B_0 = uniform magnetic field

B_{amp} = amplified magnetic field on scale s

E = particle energy in eV

Condition for acceleration:

Larmor radius in B_0

$$\frac{B_{amp}^2}{B_0^2} > \frac{r_{g0}}{s}$$

Can tolerate small *s* if magnetic field is strongly amplified

Option 3 continued: A consistent set of parameters

$$\frac{B_{amp}^2}{B_0^2} \sim \frac{r_{g0}}{s}$$

B_0 = uniform magnetic field = 1 μG

B_{amp} = amplified magnetic field (on scale s) = 100 μG

r_{g0} = Lamor radius of proton with energy 400GeV in B_0

s = Lamor radius of proton with energy 4GeV in B_{max}

In this picture:

Shock compressed uniform perpendicular field is 1 μG

Magnetic field amplified to 100 μG

Amplified field on Larmor scale of 4GeV protons (mildly suprathermal)

Maximum CR energy of 400GeV set by:

CR mean free path in amplified field = CR Larmor radius in uniform field

Summary

Extragalactic jet termination shocks accelerate electrons to ~400GeV (typically)

Why this energy so low?

x Not due to Hillas limit (option 1)

x Not due to synchrotron cooling (option 2)

Need inconceivably
Slow acceleration

√ Amplified Larmor turbulence at perpendicular shock fits data (option 3)

$$\frac{\nu}{\omega_{g0}} = \frac{scB_{amp}^2}{E(eV)B_0} \quad \Rightarrow \quad E(eV) = \frac{scB_{amp}^2}{B_0}$$