PARTICLE ACCELERATION AND MAGNETIC FIELD AMPLIFICATION IN THE HOTSPOTS OF FR II GALAXIES

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High Energy Processes in Relativistic Outflows V
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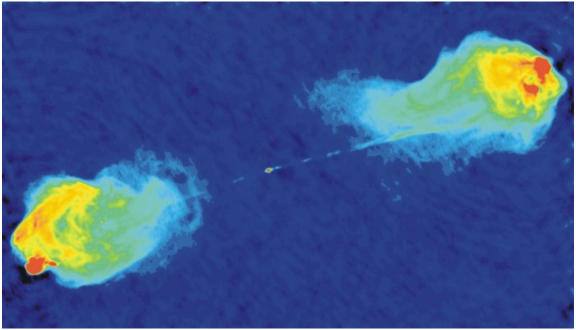
OUTLINE

MOTIVATION AND AIMS

- Active galactic nuclei (AGN) are candidates to be sources of UHECR.
- We are interested in studying diffusive shock acceleration (DSA) in the hotspots of powerful AGN jets.
- We model the thin radio emission in the hotspots of powerful radiogalaxies.

HOTSPOTS

Bright (synchrotron) radio knots of $\sim 1 - 10$ kpc embedded in larger lobes of shocked plasma.

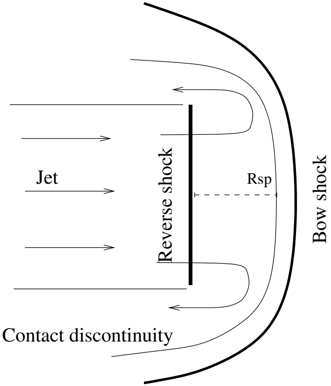


Cygnus A -VLA-

JET TERMINATION SHOCKS

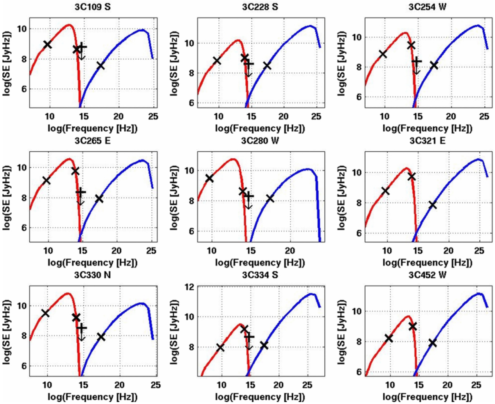
- Reverse shock in the jet ($v_{\rm shock} \sim v_{\rm j}$).
- Bow shock in the external medium ($v_{\rm bs} \ll v_{\rm j}$).

- Particles accelerated in the reverse shock radiate in the downstream region.



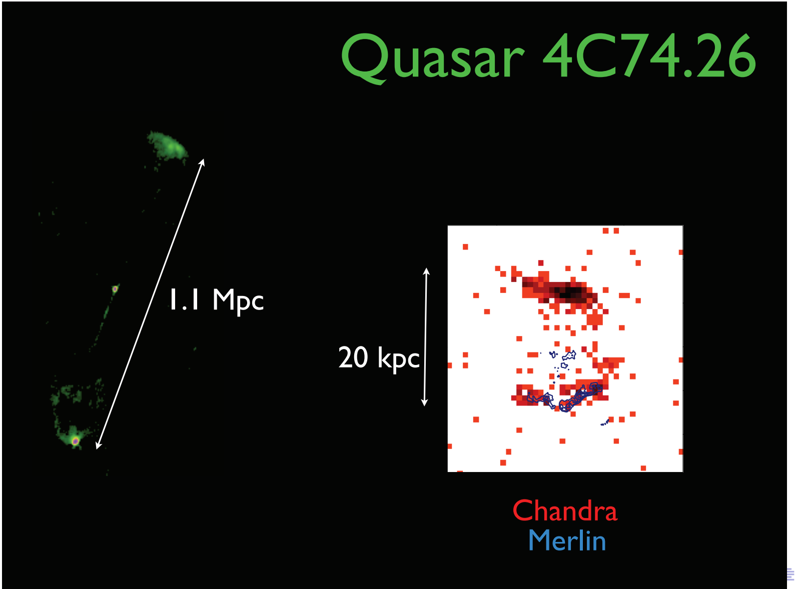
MULTI-WAVELENGTH EMISSION

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



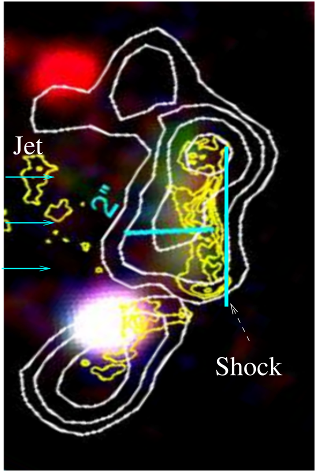
(Werner et al. 2012)

AN INTERESTING SOURCE



MULTI-WAVELENGTH DATA

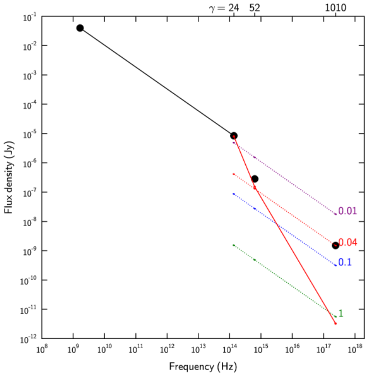
- Radio (MERLIN): yellow contours
- IR (Gemini-NIRI): red
- IR (Gemini-GMOS): green
- Optical (WHT): blue
- X (Chandra): white contours



(Adapted from Erlund et al. 2010)

NON-THERMAL ELECTRONS

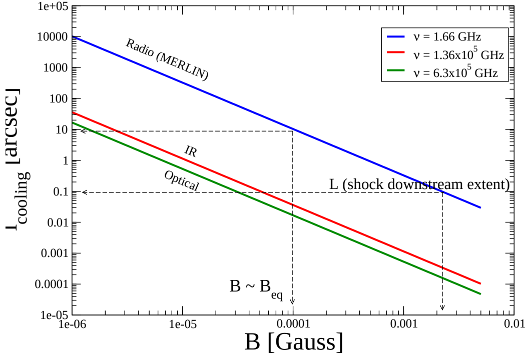
- Radio-to-IR spectral index: $\alpha = 0.75$ (p=2.5)
- Steep IR-to-optical spectrum: synchrotron turnover $\nu_{\rm c}$.
- Maximum energy of electrons: $E_{e,\max} = \gamma(\nu_{\rm c}) m_e c^2$.



(Erlund et al. 2010)

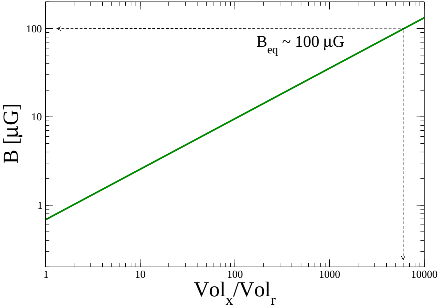
RADIO-TO-OPTICAL: SYNCHROTRON

- 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 $l_{\mathrm{cooling}} \sim 12'' \left(\frac{\nu}{\mathrm{GHz}}\right)^{-0.5} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-1.5} \left(\frac{v_{\mathrm{shock}}}{c/3}\right)$



X-RAYS: UPSCATTERING OF CMB PHOTONS -IC-

- IC cooling length $\gg 10$ arcsec.
- Adiabatic expansion is the dominant cooling mechanism.



MORE SOURCES

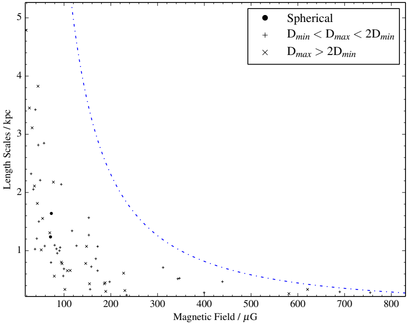
Is 4C74.26 the only source with a large aspect ratio?

HIGHLY RESOLVED HOTSPOTS @ 8.4 GHZ

- Synchrotron cooling length

$$\frac{l_{8.4}}{\mathrm{kpc}} \sim 25 \left(\frac{\nu}{8.4\,\mathrm{GHz}}\right)^{0.5} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-1.5} \left(\frac{v_{\mathrm{shock}}}{c/3}\right).$$

- Observed shock downstream length vs B_{eq}



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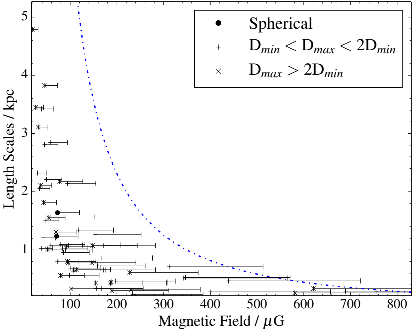
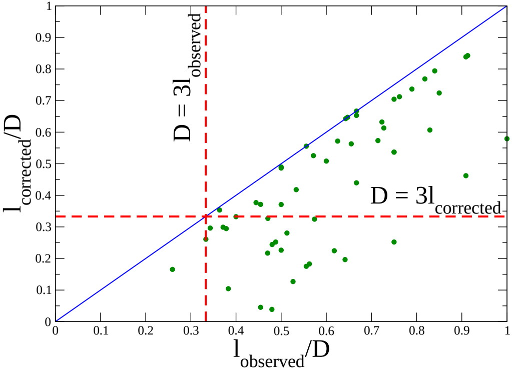


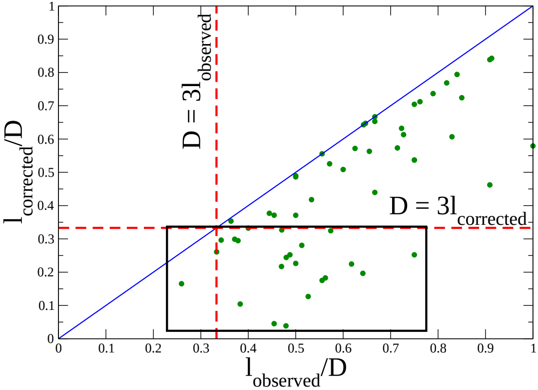
(REAL) SIZE DOWNSTREAM THE SHOCK

- Hotspots can be modelled as cylinders:
  $l_{\text{corrected}} = \frac{l_{\text{observed}} - D\cos(\theta)}{\sin(\theta)}$.
- We calculate the maximum inclination angle θ_{max}.



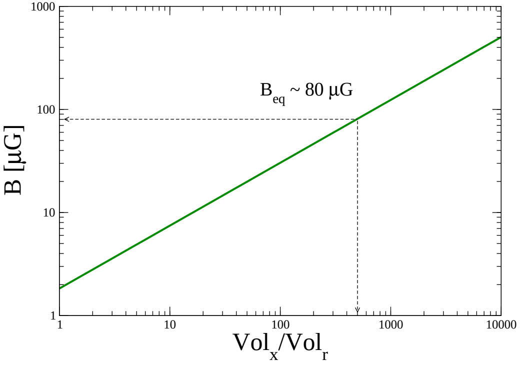
(REAL) SIZE DOWNSTREAM THE SHOCK

Advection can be ruled out for those sources with $D > 3l_{\mathrm{corrected}}$



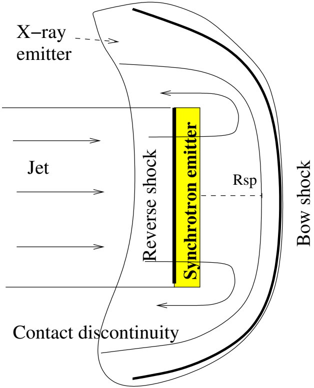
X-RAY EMISSION: IC-CMB

$$\frac{V_x}{V_r} > 1$$



HOTSPOTS AS MAGNETIC DAMPING REGIONS

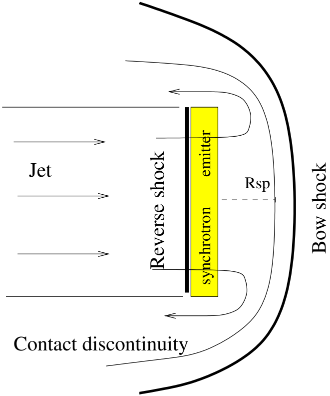
- Thin synchrotron (radio) emitter: slow synchrotron cooling
- Larger X-ray emission region: determined by advection



The very thin downstream radio extent must be determined by factors other than synchrotron cooling and adiabatic expansion.

MAGNETIC FIELD AMPLIFICATION IN HOTSPOTS

Compact synchrotron emitter: **region where the magnetic field is amplified by plasma instabilities.**



FROM OBSERVATIONS TO PLASMA PHYSICS

Synchrotron turnover at ν_c: the maximum energy of non-thermal electrons is

$$\gamma_\mathrm{c} \sim 4.5 \times 10^5 \left(\frac{\nu_\mathrm{c}}{10^{14}\,\mathrm{Hz}}\right)^{0.5} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-0.5} .$$

- Synchrotron cooling: $t_\mathrm{acc} = t_\mathrm{synch}$

$$\frac{s}{\mathrm{cm}} \sim 7 \times 10^5 \left(\frac{\nu_\mathrm{c}}{10^{14}\,\mathrm{Hz}}\right)^{1.5} \left(\frac{v_\mathrm{shock}}{c/3}\right)^{-1} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-1.5}$$

- Hillas constraint: $t_\mathrm{acc} = R_\mathrm{j}/v_\mathrm{sh}$:

$$\frac{s}{\mathrm{cm}} \sim 3.7\times10^5 \left(\frac{\nu_\mathrm{c}}{10^{14}\,\mathrm{Hz}}\right) \left(\frac{R_\mathrm{j}}{100\,\mathrm{pc}}\right)^{-1} \left(\frac{v_\mathrm{shock}}{c/3}\right)^{-1} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-3}$$

FROM OBSERVATIONS TO PLASMA PHYSICS

- In lepto-hadronic jets, s must be similar or larger than the ion skin depth

$$\frac{c}{\omega_{\rm pi}} \sim 2.3 \times 10^9 \left(\frac{n}{10^{-4}\,{\rm cm}^{-3}}\right)^{-0.5} \;{\rm cm}.$$

$\gamma_{\rm c}$ must be determined by factors other than synchrotron cooling and the Hillas constraint.

- If $s = c/\omega_{\rm pi}$:

$$\frac{D}{D_{\rm Bohm}} \sim 10^4 \left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)^{0.5} \left(\frac{B}{100\,\mu{\rm G}}\right)^{-1.5} \left(\frac{n}{10^{-4}\,{\rm cm}^{-3}}\right)^{0.5}$$

LIMIT ON ION ACCELERATION

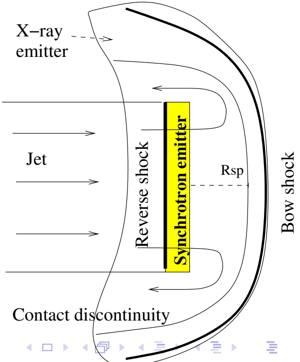
- Protons can be accelerated to higher energies than electrons because their radiative losses are minimal.
- $D/D_{\rm Bohm} \sim 10^4$ is valid also for protons with energy $\sim \gamma_{\rm c} m_p c^2$.
- The Hillas parameter is reduced by a factor $\sim (D/D_{\rm Bohm})^{-1}$.
- Proton-energy upper limit

$$\boxed{E_{p,{\rm max}} \sim 100 \text{ EeV} \left(\frac{D}{D_{\rm Bohm}}\right)^{-1} \sim 10 \text{ PeV}}$$

CONCLUSIONS I

We model the radio to X-ray emission in hotspots of FR II galaxies.

- Compact radio emission region: it is too thin to be the result of fast synchrotron cooling.
- Extended X-ray emission region: determined by adiabatic expansion.



- **The thin synchrotron emitter is determined by damping of the magnetic field.**

CONCLUSIONS II

- Turnover of the synchrotron spectrum at $\nu_{\rm c} \gtrsim 10^{14}$ GHz requires $\lambda \gg r_{\rm g}$ (i.e. the acceleration mechanism is slow):

$$\frac{D}{D_{\rm Bohm}} \sim 10^4 \left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)^{0.5} \left(\frac{B}{100\,\mu{\rm G}}\right)^{-1.5} \left(\frac{n}{10^{-4}\,{\rm cm}^{-3}}\right)^{0.5}$$

- If ions are accelerated as well, the maximum proton energy at the jet termination shock is only 10 PeV instead of the 100 EeV indicated by the Hillas parameter.

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

EXTRA SLIDES

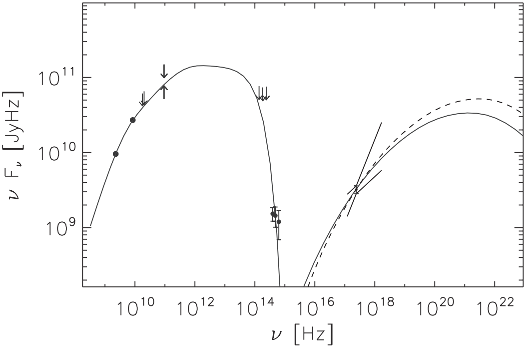
Extra slides

RADIO-TO-OPTICAL SYNCHROTRON EMISSION

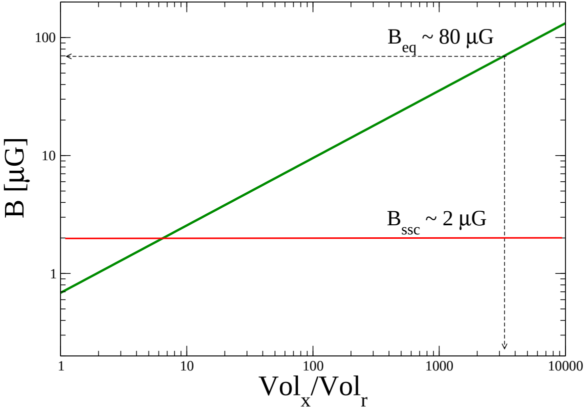
Break $\nu_{\rm br} : t_{\rm acc} = t_{\rm syn} \Rightarrow$

$$\frac{B}{\mu{\rm G}} \sim 100 \left(\frac{\nu_{\rm br}}{10\,{\rm GHz}}\right)^{1/3} \left(\frac{v_{\rm sh}}{10^{10}\,{\rm cm\,s^{-1}}}\right)^{2/3} \left(\frac{L}{\rm kpc}\right)^{-2/3}$$

Turnover $\nu_{\rm c} : t_{\rm adv} = t_{\rm syn} \Rightarrow \frac{\lambda}{L} \sim 0.05 \left(\frac{\nu_{\rm br}}{\nu_{\rm c}}\right) \left(\frac{v_{\rm sh}}{10^{10}\,{\rm cm\,s^{-1}}}\right)$



IC-CMB + SSC



MAGNETIC FIELD AMPLIFICATION IN HOTSPOTS (I)

- Synchrotron turnover $\nu_{\rm c} \sim 10^{14}$ GHz: the maximum energy of non-thermal electrons is

$$\gamma_{\rm max} \sim 4.5 \times 10^5 \left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)^{0.5} \left(\frac{B}{100\,\mu{\rm G}}\right)^{-0.5} .$$

- The Larmor radius of these electrons is

$$\frac{r_{\rm g}(\gamma_{\rm max})}{\rm cm} \sim 9 \times 10^{12} \left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)^{0.5} \left(\frac{B}{100\,\mu{\rm G}}\right)^{-1.5} .$$

WEIBEL INSTABILITIES

- The amplified magnetic field is structured on a scale s of the order of ion skin depth

$$\frac{c}{\omega_{\mathrm{pi}}} \sim 2.3 \times 10^{9} \left(\frac{n}{10^{-4}\,\mathrm{cm}^{-3}} \right)^{-0.5} \mathrm{cm}.$$

- Quickly decay behind the shock (Chang et al. 2008, Lemoine 2013)

$$t_{\mathrm{d}} \sim \left(\frac{s}{c/\omega_{\mathrm{pe}}} \right)^{2} \frac{s}{c}.$$

- $B \propto z^{-1}$ accounts for the afterglow emission in (ultra relativistic) GRB jets (Piran & Sari).
- Can Weibel instabilites explain also the thin downstream extent of the jet termination shocks in FR II jets?

WEIBEL INSTABILITIES + SYNCHROTORN COOLING

- $t_{\rm acc} = t_{\rm synch}$

$$\gamma_{\rm max,syn} \sim 5.1 \times 10^3 \, s^{1/3} \left(\frac{v_{\rm sh}}{c/3}\right)^{1/3} .$$

- $\gamma_{\rm max} = \gamma_{\rm max,syn}$:

$$\frac{s}{\rm cm} \sim 7 \times 10^5 \left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)^{1.5} \left(\frac{v_{\rm sh}}{c/3}\right)^{-1} \left(\frac{B}{100\,\mu{\rm G}}\right)^{-1.5}$$

$$s \sim 3 \times 10^{-4} \frac{c}{\omega_{\rm pi}}$$

WEIBEL INSTABILITIES + HILLAS CONSTRAINT

- By comparing the acceleration timescale $t_{\rm acc}$ with a typical timescale $R_{\rm j}/v_{\rm sh}$:

$$\frac{\lambda}{\rm cm} \sim \left(\frac{R_{\rm j}}{20}\right)\left(\frac{v_{\rm sh}}{c/3}\right) \sim 1.5\times10^{20}\left(\frac{R_{\rm j}}{\rm kpc}\right)\left(\frac{v_{\rm sh}}{c/3}\right)$$

- $\lambda \sim r_{\rm g}^2/s$: upper limit for the electrons maximum energy

$$\gamma_{\rm max,H} \sim 735\, s^{0.5}\left(\frac{R_{\rm j}}{\rm kpc}\right)^{0.5}\left(\frac{v_{\rm sh}}{c/3}\right)^{0.5}\left(\frac{B}{100\,\mu{\rm G}}\right)$$

- $\gamma_{\rm max} = \gamma_{\rm max,H}$:

$$\frac{s}{\rm cm} \sim 3.7\times10^5\left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)\left(\frac{R_{\rm j}}{100\,{\rm pc}}\right)^{-1}\left(\frac{v_{\rm sh}}{c/3}\right)^{-1}\left(\frac{B}{100\,\mu{\rm G}}\right)^{-3}$$