Acceleration of UHECRs in AGN jets

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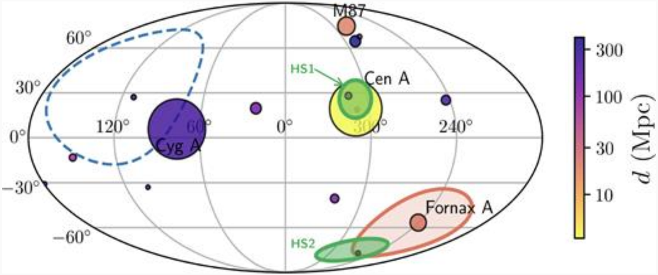
UHECRs arrival directions

Pierre Auger and Telescope Array anisotropies correlates with AGN and starburst galaxies



Matthews, Bell, Blundell, Araudo (2018)

But... starburst galaxies do not satisfy the minimum power requirement

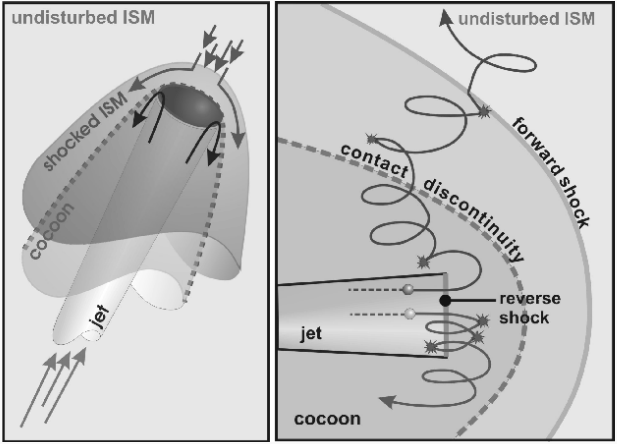
$$L > 4 \times 10^{42} \left(\frac{Z}{6}\right)^{-2} \left(\frac{E}{100\,\mathrm{EeV}}\right)^{2} \left(\frac{v}{c}\right)^{-1} \mathrm{erg\,s^{-1}}$$

Particle acceleration in the hotspots of AGN jets

Reigning paradigm

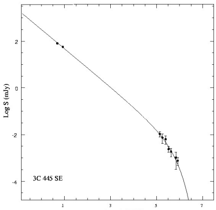
- $E_{e,\mathrm{max}}$ is determined by synchrotron losses ($t_{\mathrm{acc}} = t_{\mathrm{synchr}}$)
- Hadronic losses are minimal; protons are accelerated up to E_{H} and escape

$$\left(\frac{E_{\mathrm{Hillas}}}{100\,\mathrm{EeV}}\right) = Z\left(\frac{v}{c}\right)\left(\frac{B}{100\mu\mathrm{G}}\right)\left(\frac{L}{\mathrm{kpc}}\right)$$



Electrons maximum energy in the hotspots

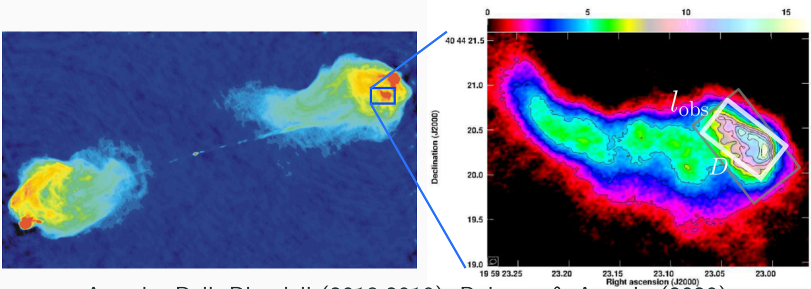
$$E_{e,\rm max} \sim 0.2 \left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)^{0.5} \left(\frac{B}{100\,\mu{\rm G}}\right)^{-0.5} \;{\rm TeV}$$



Prieto et al. (2012)

If synchrotron losses stop electron acceleration...

$$\boxed{\lambda \sim 100 \left(\frac{v_{\rm sh}}{c/3}\right)^{2} \left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)^{-1/2} \left(\frac{B}{100\,\mu{\rm G}}\right)^{-3/2} \;{\rm pc}}$$



Araudo, Bell, Blundell (2018,2019), Pulnova & Araudo (2020)

Mean-free path upper-limit

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

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

$$\boxed{\lambda_{\rm max} \equiv \frac{r_{\rm g}^2(E_{e,\rm max})}{c/\omega_{\rm pi}} \sim 0.1 \left(\frac{\nu_{\rm c}}{10^{14}\,{\rm Hz}}\right)\left(\frac{B}{100\,\mu{\rm G}}\right)^{-3}\left(\frac{n_{\rm j}}{10^{-4}\,{\rm cm^{-3}}}\right)^{0.5}\ {\rm pc}}$$

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

$B_{\rm max}$ **is insufficient to explain the synchrotron fluxes in the hotspots.** **Therefore, the assumption $t_{\rm acc} = t_{\rm synchr}$ is incorrect.**

Constraining the maximum energies

- In perpendicular shocks, the available time for magnetic field amplification and particle acceleration is $t_\perp = r_{\mathrm{g0}}/c$
- The condition $\Gamma_{\max} t_\perp > 5$ leads to

$$\frac{E_{p,\max\perp}}{\mathrm{TeV}} \sim 40 \left[\left(\frac{\eta_{\mathrm{p,tot}}}{0.1} \right) \left(\frac{B_0}{\mu\mathrm{G}} \right)^{-1} \left(\frac{v_{\mathrm{dr}}}{c} \right) \left(\frac{n_{\mathrm{i}}}{10^{-4}\,\mathrm{cm}^{-3}} \right)^{\frac{1}{2}} \right]^{\frac{1}{s-2}}$$

- By setting $E_{p,\max\perp} = E_{e,\max}$

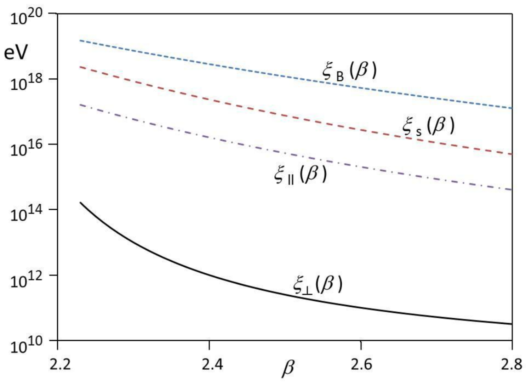
$$\frac{B_0}{\mu\mathrm{G}} \sim \left(\frac{\nu_c}{10^{14}\mathrm{Hz}} \right)^{-s+2} \left(\frac{B_{\mathrm{eq}}}{100\mu\mathrm{G}} \right)^{s-2} \left(\frac{\eta_{\mathrm{p.tot}}}{0.1} \right) \frac{v_{\mathrm{dr}}}{c} \left(\frac{n_i}{10^{-4}\mathrm{cm}^{-3}} \right)^{1/2}$$

In unperturbed magnetic field $B_0 \sim 0.1 - 1\ \mu$G and equipartition fields $(U_{\mathrm{mag}} = U_{\mathrm{nt}})$ $B_{\mathrm{eq}} \sim 100\,\mu$G, we find $E_{p,\max} \sim 1 - 10$ TeV in the hotspots of AGN jets (Araudo et al, in prep.)

Relativistic plasmas are inefficient accelerators

Three main effects limit the maximum energy to which CR can be accelerated by relativistic shocks (Bell, Araudo, Matthews, Blundell, 2018):

- Steep CR spectrum ($N \propto E^{-\beta}, \beta > 2$)
- Small-scale turbulence (s)
- Quasi-perpendicular shocks ($\mathrm{B}_0 \perp \mathrm{v}_{\mathrm{sh}}$)



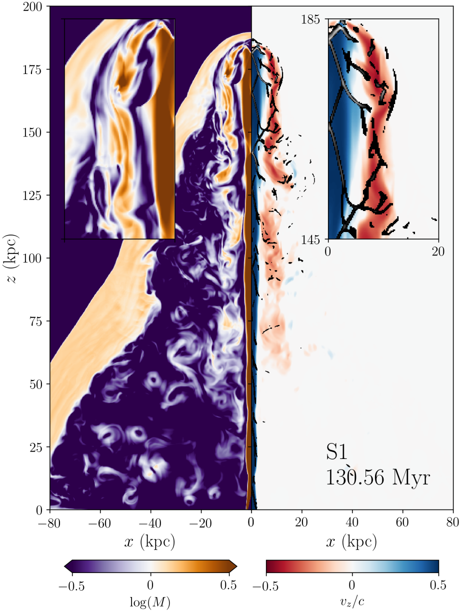
Therefore... if UHECRs are accelerated by shocks, then shocks must be mildly relativistic

Mildly relativistic shocks in AGN jets

Shocks in AGN backflows

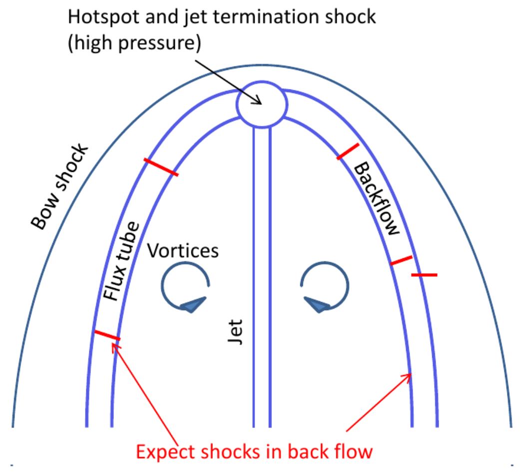
- We performed 2D and 3D HD simulations with PLUTO
- Multiple moderately strong shocks occur along the backflow

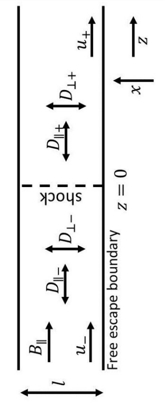
$\langle r_{\mathrm{sh}} \rangle \sim 2$ kpc
$\langle v_{\mathrm{sh}} \rangle \sim 0.2c$
$\langle B \rangle \sim 0.1$ mG



Matthews, Bell, Blundell & Araudo (2019)

Fermi acceleration in flux tubes





Bell, Matthews, Blundell & Araudo (2019)

Maximum energy of particles

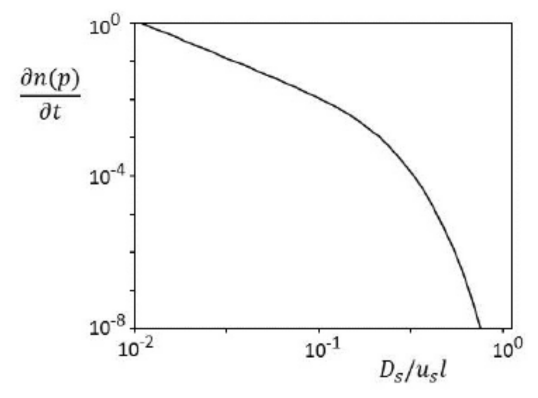
In an infinite flux tube particles can only escape from the sides by diffusing across the magnetic field[1]

CRs can reach the Hillas energy even when Bohm diffusion is not achieved

$$D_{\|} = D_{\mathrm{Bohm}} \omega_{\mathrm{g}} \tau_{\mathrm{scat}}$$
$$D_{\perp} = \frac{D_{\mathrm{Bohm}}}{\omega_{\mathrm{g}} \tau_{\mathrm{scat}}}$$

$$D_{\|} D_{\perp} = D_{\mathrm{Bohm}}^2$$

$$\boxed{E_{\mathrm{max}} = 0.6uBL \sim 0.6E_{\mathrm{H}}}$$



Bell, Matthews, Blundell & Araudo (2019)

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[1] See Lemoine (2019)

AGN jet mass loading by stellar winds

- UHECRs may consist of nuclei with various charges and masses
- The composition of AGN jets can be enriched by the interaction with stars and stellar clusters

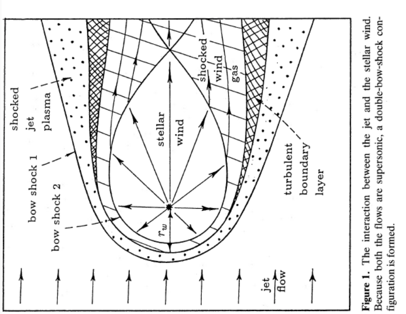
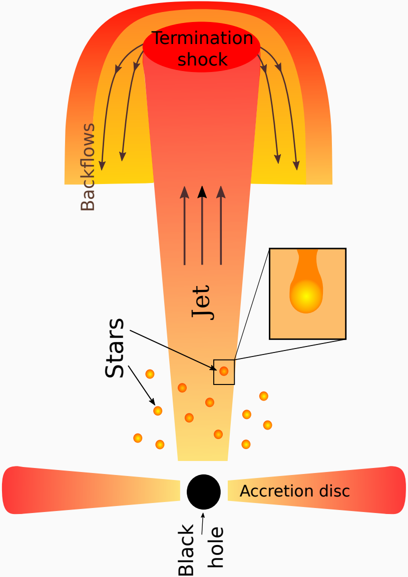


Figure 1. The interaction between the jet and the stellar wind. Because both the flows are supersonic, a double-bow-shock configuration is formed.

Komissarov (1994)



Credit: A.L Muller

Conclusions

AGNs as possible sources of UHECRs

Hotspots

- Based on one observable (ν_c) and one physical constraint ($s \geq c/\omega_\mathrm{pi}$), we found that $E_{e,\max}$ **cannot be determined by synchrotron losses**, as usually assumed
- We show that $E_{p,\max}$ (and $E_{e,\max}$) can be constrained by the condition $\Gamma_\max r_\mathrm{g0}/c > 5$ (in quasi-perpendicular shocks)

Backflows

Flux tubes in the backflows of AGN jets are a suitable environment for acceleration of UHECRs.

The Hillas energy is achieved even when Bohm diffusion doesn't apply

$$\boxed{E_\max \sim 0.6 E_\mathrm{Hillas}}$$

The UHECR hotspot in M82 can be the result of reflection of UHECRs accelerated in the backflows of Centaurus A 20 Myr ago (Bell & Matthews, 2021)

Questions?