Particle acceleration and magnetic field amplification in the jet termination shocks at all scales

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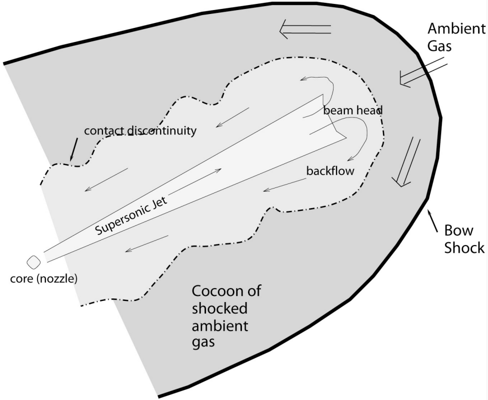
Introduction

Shocks in jets

- Shocks along the jet (internal), in the termination region, and in the backflows
- Shocks are efficient particle accelerators
- Cosmic-ray currents amplify the magnetic field (Bell 2004)

In this talk:

1. Are protostellar jets gamma-ray emitters?
2. Are AGNs sources of UHECRs?



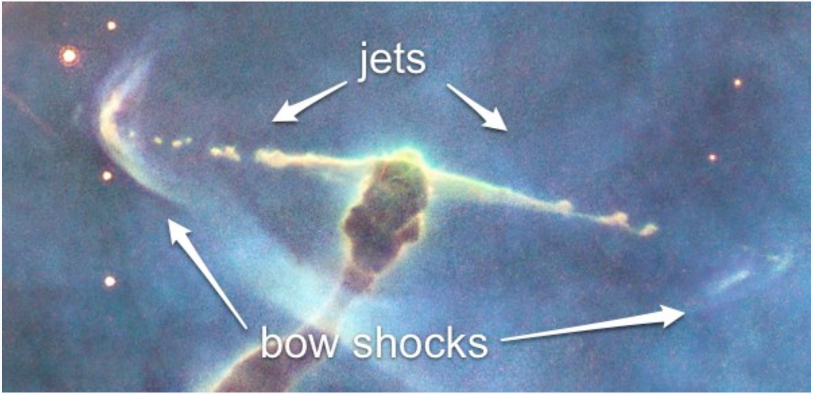
Worrall (2002)

Protostellar jets

Protostellar jets

Increasing population of **non-thermal protostellar jets**

$$\frac{U_\mathrm{e}}{\mathrm{erg\,cm^{-3}}} \sim 5{\times}10^{-8} \left(\frac{d}{\mathrm{kpc}}\right)^{2} \left(\frac{S_\nu}{\mathrm{mJy}}\right) \left(\frac{R_\mathrm{j}}{10^{16}\mathrm{cm}}\right)^{-3} \left(\frac{\nu}{\mathrm{GHz}}\right)^{\frac{s-1}{2}} \left(\frac{B_\mathrm{s}}{\mathrm{mG}}\right)^{-\frac{s+1}{2}}$$



Credit: NASA, ESA, M. Livio and the Hubble 20th Anniversary Team

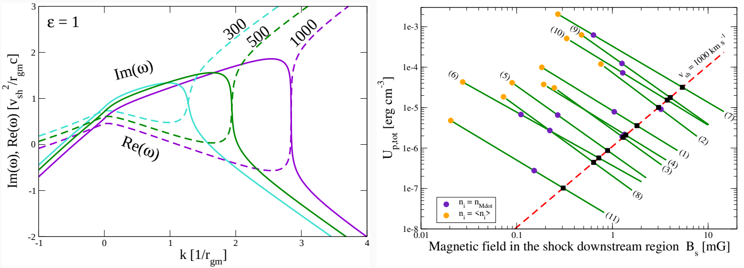
Magnetic field amplification in YSO jets

We consider a sample of 11 non-thermal radio jets (Purser et al. 2016)

Bell instability maximum growth rate (Bell 2004, 2005):

$$\frac{\Gamma_{\rm max,NR}}{\rm s^{-1}} \sim 10^{-5}\left(\frac{\eta_p}{0.01}\right)\left(\frac{v_{\rm sh}}{1000\,{\rm km\,s^{-1}}}\right)^3\left(\frac{n_i}{10^3\,{\rm cm^{-3}}}\right)^{\frac{1}{2}}\left(\frac{E_{\rm p}}{\rm GeV}\right)^{-1}$$

$$\text{Saturation}: \quad \frac{B_{\rm sat,NR}}{\rm mG} \sim 0.3\left(\frac{U_{p,\rm tot}}{10^{-6}\,{\rm erg\,cm^{-3}}}\right)^{\frac{1}{2}}\left(\frac{v_{\rm sh}}{1000\,{\rm km\,s^{-1}}}\right)^{\frac{1}{2}}$$



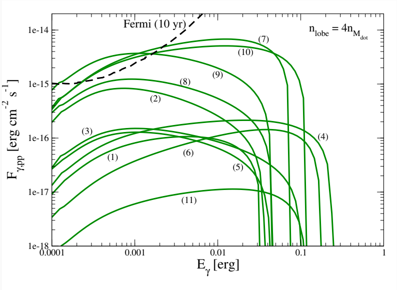
Araudo, Padovani & Marcowith (2021)

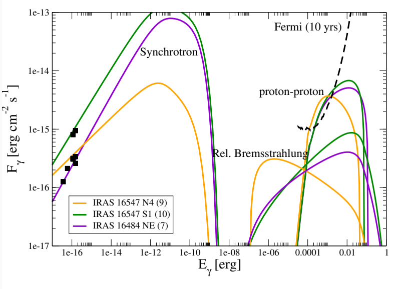
Gamma-ray emission

$E_{p,\max}$: escape of particles upstream of the shock

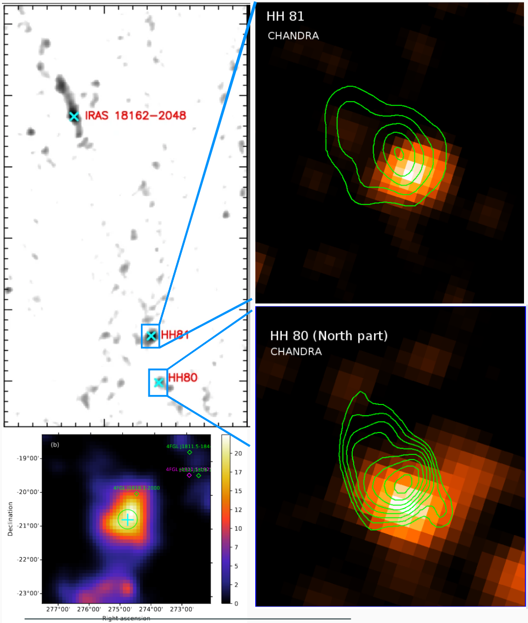
$\Gamma_{\max,\mathrm{NR}}(R_\mathrm{j}/v_\mathrm{sh}) > 5$ (Zirakashvili & Ptuskin 2008, Bell et al. 2013)

$$\frac{E_{p,\max}}{\mathrm{m_p c^2}} = \begin{cases} 70(2-\beta)\left(\frac{U_{p,\mathrm{tot}}}{10^{-5}\mathrm{erg\,cm^{-3}}}\right)\left(\frac{R_\mathrm{j}}{10^{16}\mathrm{cm}}\right)\left(\frac{n_i}{10^4\ \mathrm{cm^{-3}}}\right)^{-\frac{1}{2}} & \beta < 2 \\ 70\log\left(\frac{E_{p,\max}}{\mathrm{GeV}}\right)^{-1}\left(\frac{U_{p,\mathrm{tot}}}{10^{-5}\mathrm{erg\,cm^{-3}}}\right)\left(\frac{R_\mathrm{j}}{10^{16}\mathrm{cm}}\right)\left(\frac{n_i}{10^4\ \mathrm{cm^{-3}}}\right)^{-\frac{1}{2}} & \beta = 2 \\ \left[70(\beta-2)\frac{1}{m_p c^2}\left(\frac{U_{p,\mathrm{tot}}}{10^{-5}\mathrm{erg\,cm^{-3}}}\right)\left(\frac{R_\mathrm{j}}{10^{16}\mathrm{cm}}\right)\left(\frac{n_i}{10^4\ \mathrm{cm^{-3}}}\right)^{-\frac{1}{2}}\right]^{\frac{1}{\beta-1}} & \beta > 2 \end{cases}$$

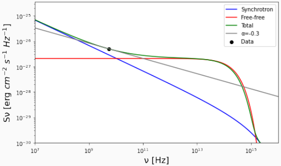


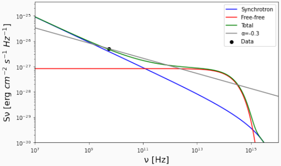


Gamma-ray emission from HH80-81[1]



Flat radio spectral indices ($\alpha = -0.3$)





(A.A., O. Tunc, A.L Muller, in prep.)

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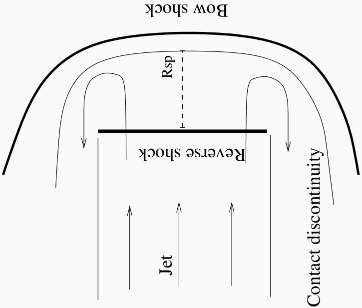
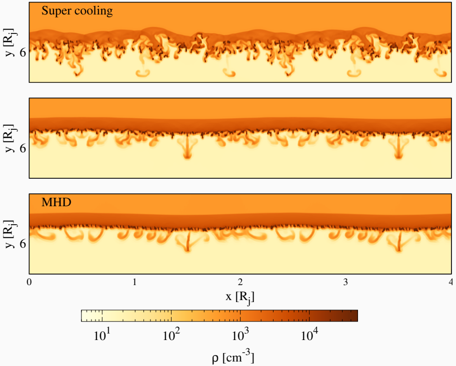
[1] Rodriguez-Kamenetzky et al. 2019, Da-Hai et al. (2022), Mohan et al. (2023)

Density enhancement in the jet termination region

Particles accelerated in the adiabatic reverse shock can diffuse up to the dense layer/clumps and emit gamma rays via π^0-decay[2]





del Valle, Araudo & Suzuki-Vidal (2022)

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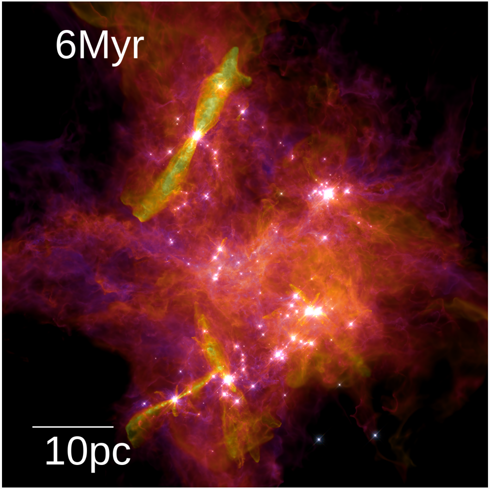
[2] New self similar solutions for the dynamics of the collision between radiative and adiabatic planar shocks (Gintrand, Moreno, Araudo, Tikhonchuk & Weber, 2021)

Collective and diffuse emission

Collective emission

- Jet speed $v_{\rm jet}(m)$
- Jet mass loss rate $\dot{M}_{\rm j}(m) = \eta \dot{M}_{\rm acc}(m)$
- Protostellar mass function dN/dm

Diffuse emission Electrons and protons that do not cool down in the jet will escape and radiate in the molecular cloud.

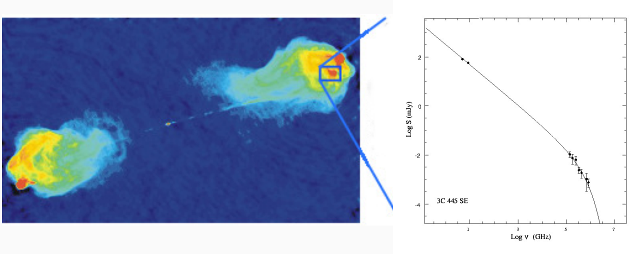


Guszejnov et al. (2020)

These particles can be a source of ionizing cosmic rays

Active Galactic Nuclei

Jet termination shocks and hotspots



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

If $E_{e,\mathrm{max}}$ is determined by synchrotron losses ($t_{\mathrm{acc}} = t_{\mathrm{synchr}}$)

$$\boxed{\lambda \leq \lambda_{\mathrm{max}} \equiv \frac{r_{\mathrm{g}}^2(E_{e,\mathrm{max}})}{c/\omega_{\mathrm{pi}}} \Rightarrow B \leq B_{\mathrm{max,s}} \sim \left(\frac{\nu_{\mathrm{c}}}{10^{14}\,\mathrm{Hz}}\right) \left(\frac{v_{\mathrm{sh}}}{c/3}\right)^{-\frac{1}{3}} \left(\frac{n_{\mathrm{jet}}}{10^{-4}\mathrm{cm}^{-3}}\right)^{\frac{1}{3}} \mu\mathrm{G}}$$

The maximum energy of e^- is not determined by synchrotron cooling, at least the jet plasma density is unreasonably large[3]

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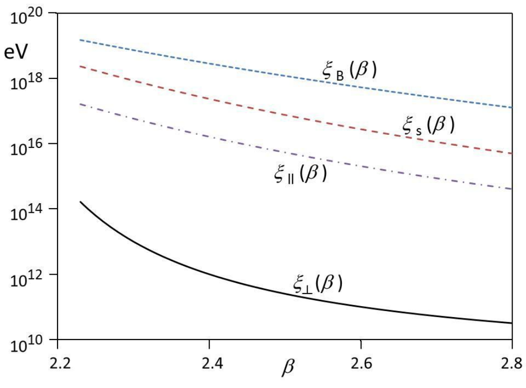
[3] AA et al. 2015, 2016, 2018

Relativistic shocks are inefficient accelerators

CRs have to amplify the magnetic field within a distance of r_{g0} downstream of the shock. The condition $\Gamma_{\mathrm{max}}(r_{\mathrm{g0}}/c) > 10$ leads to

$$\frac{E_{p,\mathrm{max}\perp}}{\mathrm{eV}} = \xi_\perp \left(\frac{B_0}{\mu\mathrm{G}}\right)^{-\frac{1}{\beta-2}} \left(\frac{n_{\mathrm{jet}}}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{\frac{1}{2\beta-4}}, \quad \mathrm{where}\, \xi_\perp = 10^{\frac{9\beta-16.8}{\beta-2}}$$

- Steep CR spectrum ($\beta > 2$): ξ_{B}
- Small-scale turbulence (s): ξ_{s}
- Quasi-perpendicular shocks: $\xi_\perp$ or $\xi_\parallel$ when $B < B_{\mathrm{crit}}$



If UHECRs are accelerated by shocks, then shocks must be mildly relativistic (Bell et al. 2018, AA et al. in prep.)

Mildly relativistic shocks in the backflows

Numerical study shows that (Matthews, Bell, Blundell, AA 2019)

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

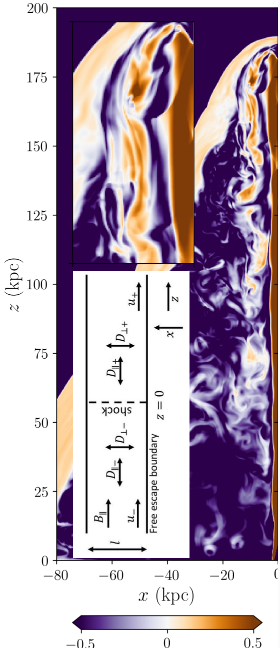
Infinite flux tube: particles can only escape from the sides by diffusing across the magnetic field (Bell, Matthews, Blundell, AA, 2019)

$$D_\parallel = D_{\rm Bohm}\omega_{\rm g}\tau_{\rm scat} \qquad D_\perp = \frac{D_{\rm Bohm}}{\omega_{\rm g}\tau_{\rm scat}}$$

$$D_\parallel D_\perp = D_{\rm Bohm}^2$$

$$\tau_{\rm acc} = 20D_\parallel/u_{\rm s}^2 \qquad \tau_{{\rm diff},\perp} \sim l^2/D_\perp$$

$$\tau_{\rm acc} = \tau_{{\rm diff},\perp} \Rightarrow \boxed{E_{\rm max} \sim 0.6E_{\rm Hillas}}$$



UHECRs from Centaurus A

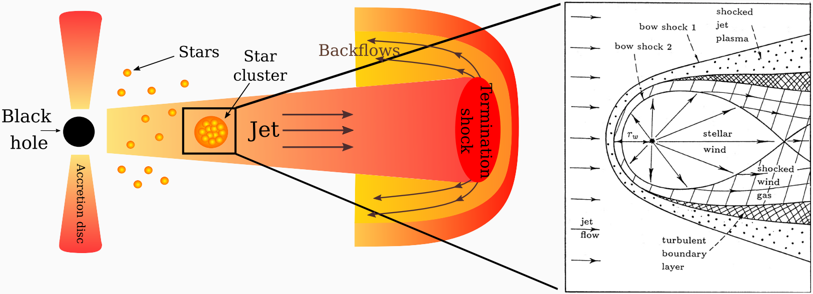
- Young stars and clusters are present in the inner region of Cen A ...
- and in a significantly larger amount in its most active phase in the past when it collided with another galaxy

Jet-mass loading by stellar winds

Double-shock structure with stagnation point at

$$\frac{r_{\rm w}}{R_{\rm jet}} = 10^{-2}\left(\frac{v_\infty}{2000\,\rm kms^{-1}}\right)^{\frac{1}{2}}\left(\frac{\dot{M}_\star}{10^{-4}\rm M_\odot\,yr^{-1}}\right)^{\frac{1}{2}}\left(\frac{L_{\rm jet}}{10^{44}\rm erg\,s^{-1}}\right)^{-\frac{1}{2}}$$

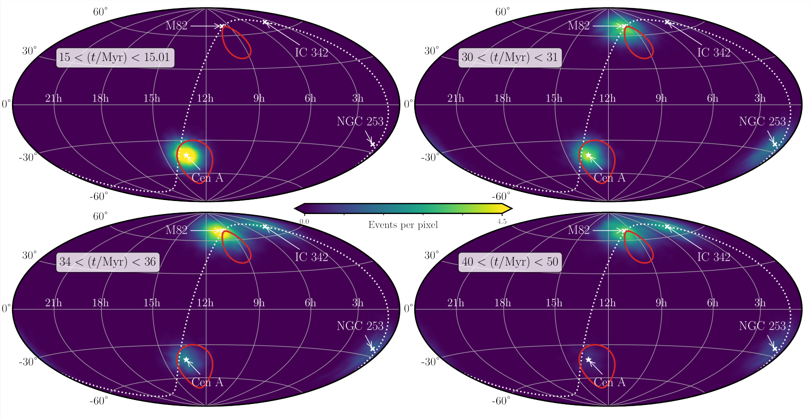
Mixing by the jet/wind interaction will contribute with a significant amount of ^{4}He, ^{16}O, ^{12}C, ^{14}N, and ^{20}N$_{\rm e}$ to Cen A jets (Wykes et al. 2015)



A.L. Müller & AA (in preparation)

Echoes of UHECRs

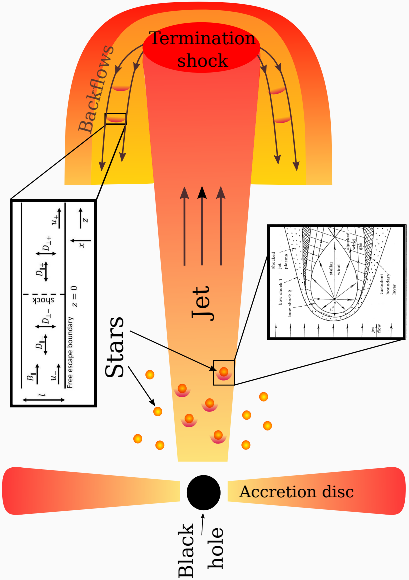
Bell & Matthews (2021) and Taylor, Matthews & Bell (2023) considered that UHECRs are accelerated in Cen A 20 Myr ago. They escape and reach M82 (and other massive galaxies) where they are reflected



Bell & Matthews (2021)

The big picture

- **Composition:** Jet-mass loading by winds of massive stars (A.L. Müller & AA - in prep.)
- **Acceleration mechanism:** Mildly-relativistic shocks in the backflows (Bell et al. 2019)
- **Sources:** Powerful FR II radiogalaxies (like Cen A 20 Myr ago)
- **Arrival direction:** Reflection in the *Council of Giants* (Bell & Matthews, 2021; Taylor et al. 2023)



Conclusions

Bell instabilities can amplify the magnetic field in the jet termination region in protostellar and radiogalaxy jets

YSO jets

- Particles accelerated in the adiabatic reverse shock diffuse up to the dense layer downstream of the radiative shock and emit γ-rays via pp inelastic collisions
- Parameters for scaled laboratory experiments are in line with plasma conditions achievable in current high-power laser facilities. An experiment will be carried out at ELI Beamlines

Backflows

- Hotspots are inefficient accelerators
- Mildly relativistic shocks in the backflows of radiogalaxies can accelerate particles up to $0.6 E_{\rm Hillas}$
- Efficient jet mass loading by stellar winds

Questions?

MHD scaling for laboratory experiments

The scaling for laboratory experiments is in line with plasma conditions achievable in currently operating high-power laser facilities, opening the door to **new means for studying novae outflows never considered before**

Parameter	YSO jet	Lab	Novae	Lab
Length scale $[R] = \mathrm{cm}$	10^{16}	0.1	6×10^{13}	0.1
Density $[n] = \mathrm{cm}^{-3}$	10^{3}	5×10^{19}	10^{9}	5×10^{19}
Pressure $[P] = \mathrm{bar}$	10^{-13}	10^{5}	8×10^{-8}	8×10^{4}
Velocity $[v] = \mathrm{km\,s^{-1}}$	1000	700	1000	1000
Magnetic field $[B] = \mathrm{G}$	10^{-4}	10^{5}	10^{-2}	10^{4}
Time scale $[t] = \mathrm{s}$	10^{8}	10^{-9}	1.2×10^{6}	2×10^{-9}
Temperature $[T] = \mathrm{eV}$	50	1000	50	1000
Localisation parameter δ	10^{-3}	6×10^{-1}	10^{-7}	6×10^{-1}
Reynolds number Re	10^{10}	10^{4}	10^{9}	10^{4}
Peclet number Pe	10^{8}	~ 1	10^{8}	~ 1
Magnetic Reynolds number Re_M	10^{18}	10^{3}	10^{17}	10^{3}
Euler number Eu	11	8	11	11
Thermal plasma beta β	50	200	10^{4}	10^{4}

Simulations for the experiment

MHD simulations performed with FLASH

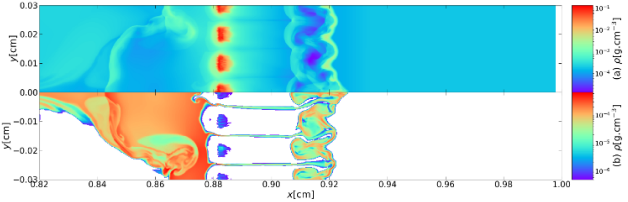


Figure 4: Profile of the total density (top) and Helium density (bottom) at *t=70 ns* for the simulation with Xenon and the grid.

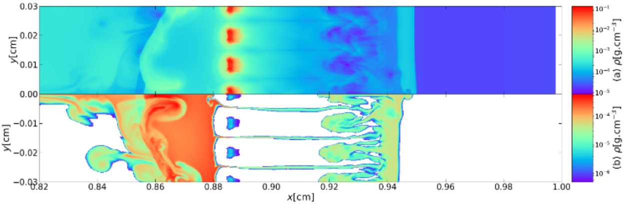


Figure 5: Profile of the total density (top) and Helium density (bottom) at *t=70 ns* for the simulation with Nitrogen and the grid.

Top view sketch of the experimental setup