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Supernova explosion within an extragalactic jet
Dynamics and radiative output

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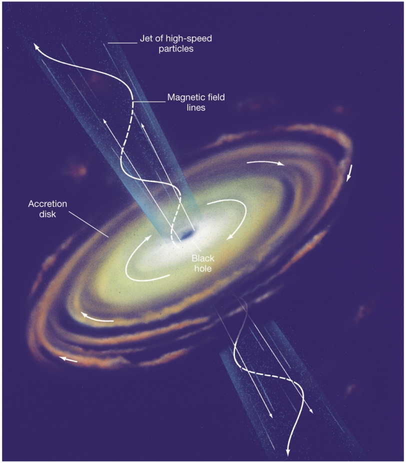
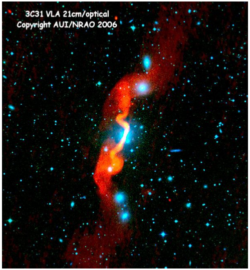
Brief summary of jets

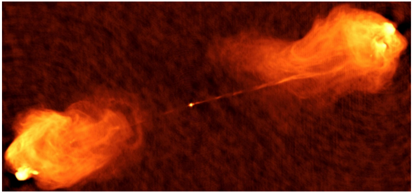
An outflow starts its propagation from a SMBH (Blandford&Zjanek 1977)



(Fanaroff&Riley 1974) classification:

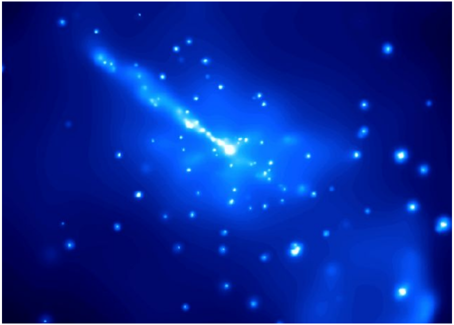


FRI: brighter close to the AGN, cooling down through the propagation



FRII: More powerful and show bright hot spot at the end of the lobes.

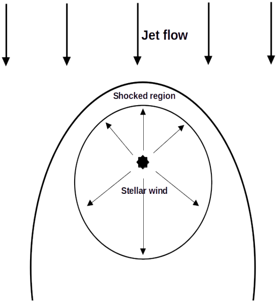
From jet deceleration to particle acceleration



Nearby galaxy Centaurus A in X-ray (Kraft et al 2001, Goodger et al 2010)

Entrainment in FRIs

Protons or heavier elements (stellar winds, clouds, SN, ambient medium)
→ inexorable mass-loading and deceleration of the jet (De Young 1986, Bowman et al. 1996)



Shocks

- Balance between 2 supersonic matching flows (Komissarov 1994, Hubbard & Blackman 2006)
- Conversion of E_k into U
  → expansion of the shock surface
- Acceleration of e^-, p or heavier ions
  → possible emissions up to γ-rays and acceleration of UHECR?

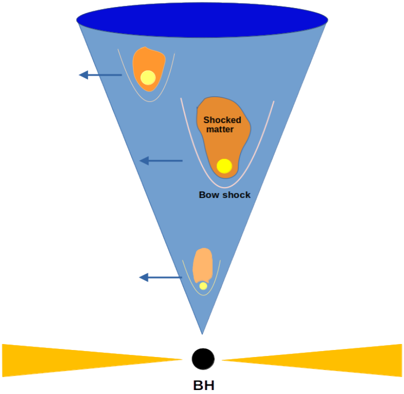
Jet/star interaction time scale with the distance from the jet base

Close to the AGN | $z < 10\,\mathrm{pc}$

- Presence of large amounts of gas
  → typically $\approx 10^3 - 10^4$ stars
  (RG, MS, AGB..)
- Interaction with the outflow short
  ($t_{\rm int} = 2R_{\rm j}/v_{\rm orb}$, typ. $\approx$ kyr) but frequent
  (short orbital period) (Kurfürst et al. 2024)
  → small mass loss per interaction

Far from the AGN | $z > \mathrm{kpc}$

- The jet has expanded
  → Jet/star interaction time scale increases (typ. $\approx$ Myr)
- Stellar population typ. $\approx 1\mathrm{star/pc^3}$
  ⇒ If RSG, eventual explosion
- few SN/century/galaxy and 0.01% of them inside the jet (Vieyro et al. 2019)



A RSG can explode within the jet flow (Bosch-Ramon 2023)
If the jet ram pressure becomes dominant over the SN ejecta
⇒ eventual disruption

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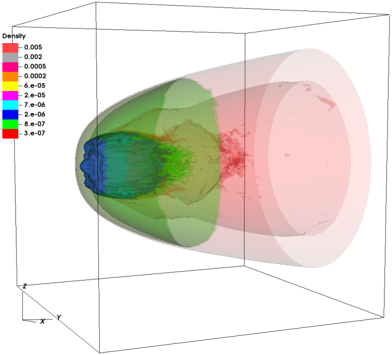
3D RHD simulations (Longo et al. 2025)



Jet properties

- $R_{\rm j} = 100\,{\rm pc}$
- $L_{\rm j} = 10^{44}\,{\rm erg\,s^{-1}}$
- $\Gamma_{\rm j} = 2$
- $h_{\rm j} = 1.1c^2$
- $\rho_{\rm j} = 6 \cdot 10^{-30}\,{\rm g/cm^3}$
- $T_{\rm j} = 2 \times 10^{11}\,K$

SN properties

- $M_{\rm SN} = 2\,M_\odot$
- $E_{\rm SN} = 10^{51}\,{\rm erg}$
- $R_{\rm SN} = 1.1\,{\rm pc}$
- $\rho_{\rm SN} = 2.4 \cdot 10^{-23}\,{\rm g/cm^3}$
- $T_{\rm SN} = 10^9\,K$
- $v_{\rm orb} = 200\,{\rm km\,s^{-1}}$

- We start $\approx 10^3\,{\rm yr}$ post explosion, located far from the jet walls
- $R_{\rm j} >> R_{\rm SN} \quad \Rightarrow R_{\rm SN} \approx 10^{-2} R_{\rm j}$
- Uniform ejecta $\rho_{\rm SN}, p_{\rm SN} >> \rho_{\rm j}, p_{\rm j}$
- Jet and ejecta: ionized gas of protons and electrons

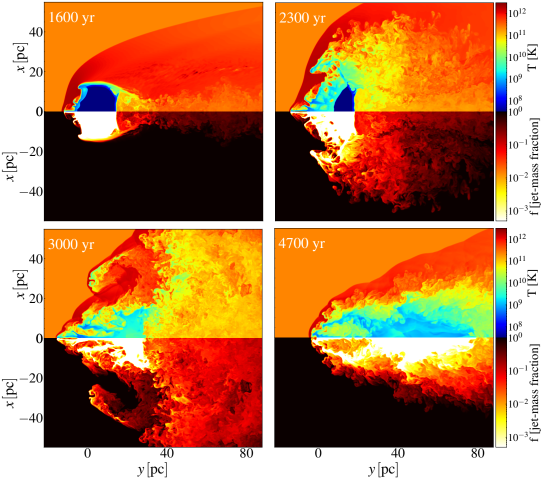
Code: `Ratpenat` (Perucho et al. 2010)

OpenMPI+OpenMP HRSC 3D RHD code, Marquina 1998 fluxes, PPM recon, Synge EoS, TVD-preserving RK

Conservative form equations $\frac{\partial U}{\partial t} + \frac{F^i}{\partial x^i} = 0$

Where $U = (D, S^j, \tau)^T$ and $F = (Dv^i, S^j v^i + p\delta^{ij}, S^i - Dv^i)$

2D cuts through the 3D physical domain



Dynamical evolution

- Free expansion phase
- Shock wave and disruption
- Important mixing
- Ejecta swept away

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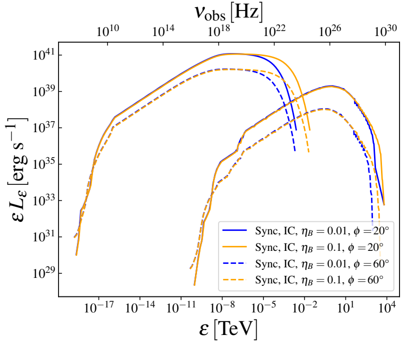
Non-thermal emission:
Simplified approach to compute the radiative output

Power emitted

- Non-thermal energy $E_{\mathrm{NT}} = \eta U_{\mathrm{cell}}$ where $\eta < 1$
- Broken power-law for the e^- distribution with a break energy given by the adiabatic time
- Inverse Compton scattering + Synchrotron

Inverse Compton scattering

- Target photons:
  → Anisotropic CMB + IR galactic background
- Approximate formula for the Thompson+Klein-Nishina regime (Khangulyan 2014, Bosch-Ramon&Khangulyan 2018)



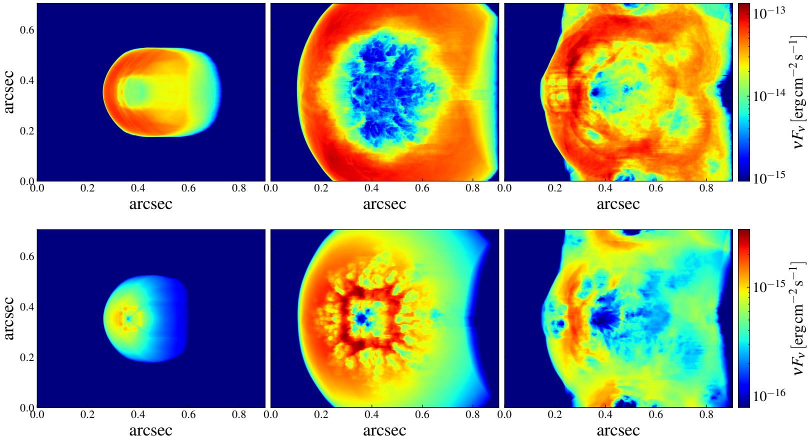
Emitted luminosity with $\eta = 0.1$

- With the given e^- distribution, we reach the PeV in IC
- The Synchrotron emission reaches $10^{41}\,\mathrm{erg\,s^{-1}}$ and the IC reaches $10^{39}\,\mathrm{erg\,s^{-1}}$

Flux on the line of sight for a source at $z = 0.007$ and $\phi = 20°$

IC
10^{27} Hz

Sync
10^{10} Hz

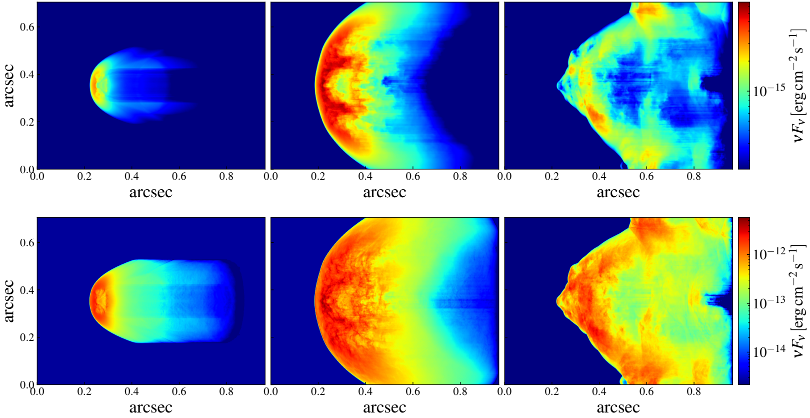


1 kyr | 2.3 kyr | 3.8 kyr

Flux on the line of sight for a source at $z = 0.007$ and $\phi = 60°$

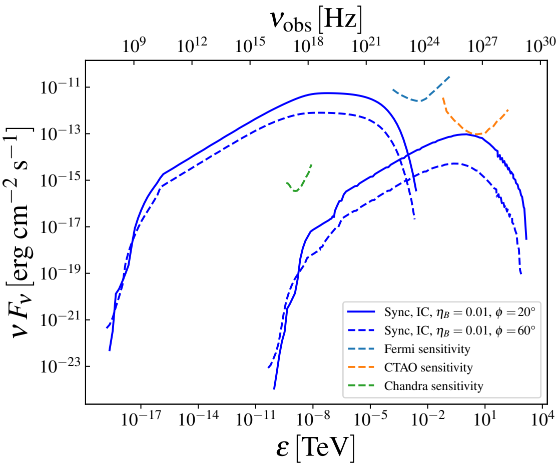
IC
10^{24} Hz

Sync
10^{18} Hz



1 kyr   2.3 kyr   3.8 kyr

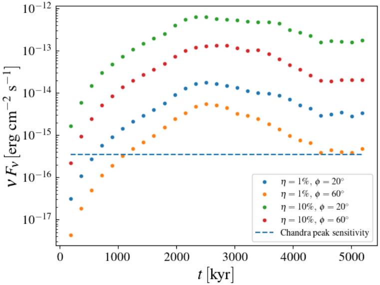
SEDs with $\phi = 20, 60°$



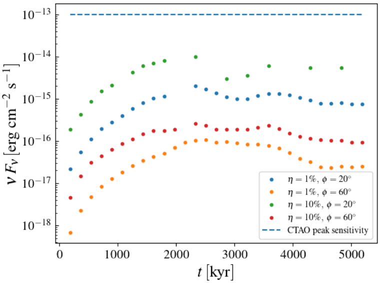
- $\eta = 0.1 \quad \eta_{\rm B} = p_{\rm B}/p_{\rm g} = 10^{-2}$
- Source at $z = 0.003$ (13Mpc) (type CenA)
- Fluxes for synchrotron and IC emission
- Possible detection of synchrotron by Chandra and IC by CTAO

Light curve with $\phi = 20, 60^\circ$ and $z = 0.007$ (31Mpc)

X-rays (10^{18} GHz)



γ-rays (10^{27} GHz)



- Internal to non-thermal energy ratio $\eta = 0.1, 0.01$
- IC close to be detectable in γ-rays
- Chandra is sensitive enough to detect the synchrotron emission for the whole duration of the interaction

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Jet/SN interaction

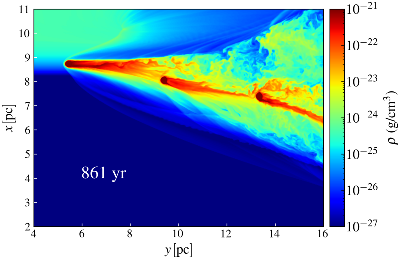
- A post-disruption expansion of the bow-shock, which covers the whole jet
- Causes a local jet drop in velocity of 40%
- Results in a mass-load of $10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$ over the interaction time scale ($\approx 10^4\,\mathrm{yr}$)

NT radiation

- For sources closer than or at 30Mpc, CTA may be able to detect the γs
- Chandra should easily detect the X-ray synchrotron
- In radio (43Ghz) peak of $0.1\,\mathrm{mJy}$ at 30 Mpc in synchrotron

Longo et al. In prep

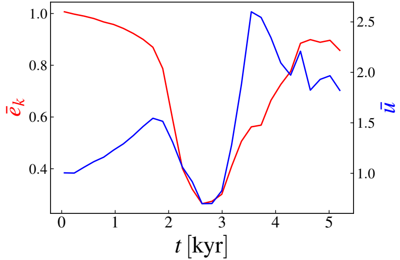
- FRIs deceleration model (Perucho 2020)
- Stars entering the jet through the jet/ISM shear layer
- Trigger mixing between the ISM and the jet
- Possible to apply the non thermal calculations to the shocked jet material



Thank you

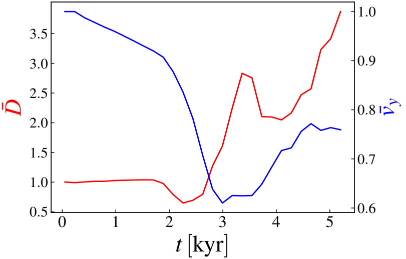
Following the time evolution of the interaction

Normalized quantities: summing across the outflow boundary and divided by the jet values



Kinetic and internal energy densities

- Global drop for both energy densities
- $u \nearrow$ whith the swept heated ejecta
- $e_k \nearrow$ with the loaded heavy matter



Lab frame density and axial velocity

- $D \nearrow$ with the entrainment of the ejecta
- $v_y \searrow$ with the disruption then $\nearrow$ with the reacceleration

RHD equations

Stress-energy tensor :
$T^{\mu\nu} = \rho h u^\mu u^\nu + p g^{\mu\nu}$
We use the Ratpenat code, which solves the conservation equations with high-resolution shock-capturing methods

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\mathbf{F^i}}{\partial x^i} = 0$$

Where $\mathbf{U} = (\mathbf{D}, \mathbf{S^j}, \tau)^\mathbf{T}$ and

$$\mathbf{F} = \begin{pmatrix} D v^i \\ S^j v^i + p\delta^{ij} \\ S^i - D v^i \end{pmatrix}$$

The conservative variables are related to the primitive ones

The rest mass density $D = \rho\Gamma$
The density momentum
$S^i = \rho h \Gamma^2 v^i$
The energy density
$\tau = \rho h \Gamma^2 - p - D$

Where we can define the 4-vector velocity $u^\alpha = \Gamma(1, v^i)$
The specific enthalpy
$h = 1 + \epsilon/c^2 + p/(\rho c^2)$
And the Lorentz factor
$\Gamma = \frac{1}{\sqrt{1 - v^i v_i / c^2}}$

RMHD equations

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\mathbf{F^i}}{\partial x^i} = 0$$

Where $\mathbf{U} = (\mathbf{D}, \mathbf{S^j}, \tau, \mathbf{B^j})^{\mathbf{T}}$ and

$$\mathbf{F} = \begin{pmatrix} D v^i \\ \rho h^* W^2 * v^j v^i + p^* \delta^{ij} - b^i b^j \\ \rho h^* W^2 v^i - b^0 b^i - \rho W v^i \\ v^i B^j - B^i v^j \end{pmatrix}$$

And we can define the other variables:

4-vector velocity $u^\alpha = \Gamma(1, v^i)$

4-vector magnetic field where

$b^0 = W(\mathbf{v} \cdot \mathbf{B})$

$b^i = \frac{B^i}{W} + v^i b^0$

And the magnetic pressure would be $|b|^2 = \frac{B^2}{W^2} + (\mathbf{v} \cdot \mathbf{B})^2$

The specific enthalpy

$h^* = 1 + \epsilon + p/(\rho) + |b|^2/\rho$

The total pressure

$p^* = p_g + p_{mag} = p + |b|^2/2$