Relativistic HD and MHD models for AGN jet propagation and deceleration

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Outline

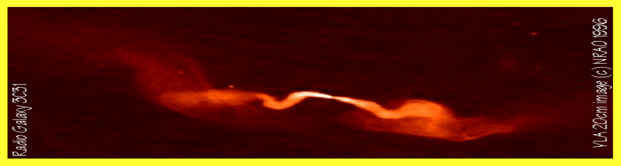
- Fanaroff-Riley classification and HYMORS
  - $\Rightarrow$ contemporary challenges in AGN jet modeling
- **Relativistic (M)HD simulations**
  - $\Rightarrow$ relativistic HD jet simulations and HYMORS
  - $\Rightarrow$ relativistic (M)HD two-component jet simulations
- Outlook

Fanaroff-Riley 1974 classification

- correlation **radio luminosity** - positions high-low surface brightness

  $\Rightarrow$ Class I – Class II transition: at well-defined $L_{178\mathrm{Mhz}}$

- FR I: brightest near core, jets in 80 %, **relativistic at parsec scale while diffuse and subrelativistic at kpc**



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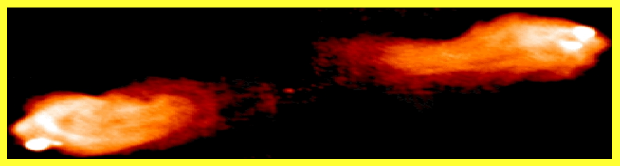
- FR II: emission in **lobes and hot spots**; narrow, highly relativistic jet

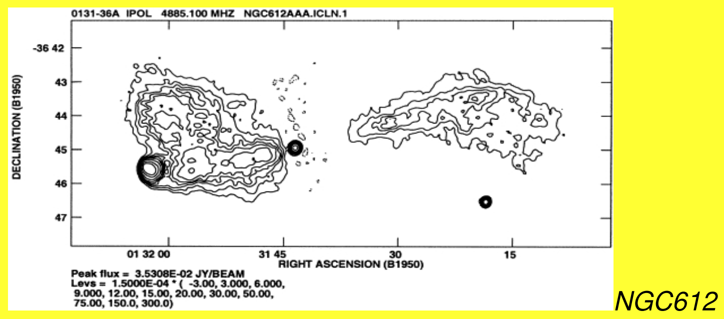


Cygnus A

- relation radio appearance - **IGM energy transport/deposition**

HYMORS

- Gopal-Krishna & Wiita 2002: **Hy**brid **Mo**rphology **R**adio **S**ources
  - ⇒ FR I appearance on one side, FR II characteristics
  - ⇒ FR I/II classification relates to **ambient medium differences**



  - ⇒ FR II lobe with hotspot to SE, diffuse jet to NW (FR I)
  - ⇒ source yields 'identical' launch conditions at each side

AGN jet challenges

- How to decelerate highly energetic (especially FR II) flows?

  $\Rightarrow$ HYMORS suggest **external medium influence**, study with axisymmetric HD jet models
- jet launch models and observations point out **transverse stratification**

  $\Rightarrow$ source region controls inner/outer jet properties

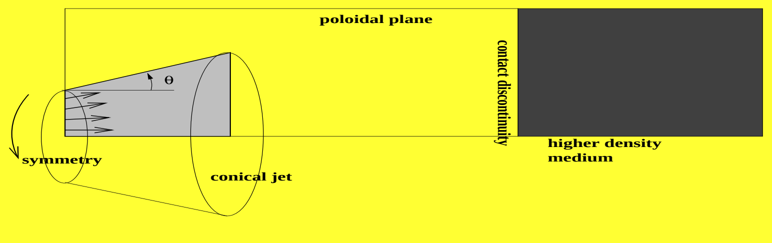
  $\Rightarrow$ FR II/FR I transition: **liability to relativistic Rayleigh-Taylor mode**

  $\Rightarrow$ relativistic 2.5D and 3D (M)HD simulations
- Magnetization of jet flows

  $\Rightarrow$ **role of helical B in collimation/propagation**

Model parameters

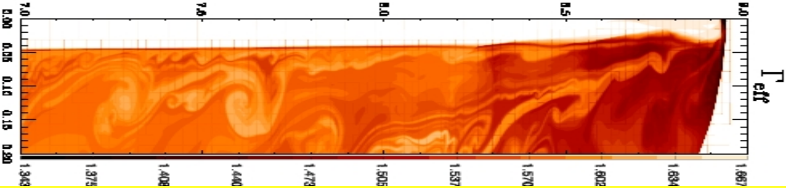
- jet kinetic energy & Lorentz factor Γ (order 10-20)
- ratio between jet/IGM inertia (density contrast)
- opening angle: cylindrical/conical models



- external medium stratification: include **density discontinuities**

  $\Rightarrow$ inevitable boundaries seperating differing regions of influence
- **special relativistic (magneto)hydro** equations

- **Relativistically correct ideal gas: effective $\gamma(T)$**
  - $\Rightarrow$ varying polytropic index: affects compression rate, shock strength
- Application: **AGN jets encountering density discontinuity**
  - $\Rightarrow$ **simulate jet propagation through layered media**
  - $\Rightarrow$ $\Gamma \simeq 20$ beam Lorentz factor, $L_{Jet,Kin} \sim 10^{46} \mathrm{e}rgs/s$.
- lower region: lighter medium $\rho_{Low}/\rho_b = 0.1496$
  - $\Rightarrow$ after 160 light crossings **zoom on jet head before jump encounter**
- **preformed jet head: ultrarelativistic state in shocked, swept-up ISM**
  - $\Rightarrow$ effect on dynamics as it penetrates denser region



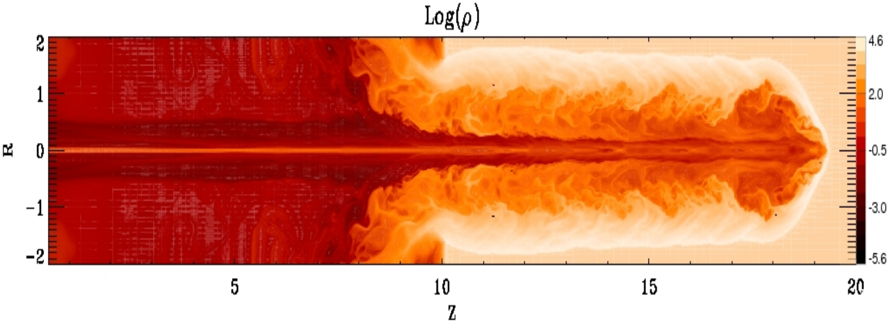
- explored differences between **low-high energy jets:** 10^{43} **or** 10^{46} $ergs/s$

  $\Rightarrow$ jet beam kinetic luminosity

$$L_{jet,Kin} = (\Gamma_b\, h_b - 1)\, \rho_b \Gamma_b \pi\, R_b^2 v_b$$

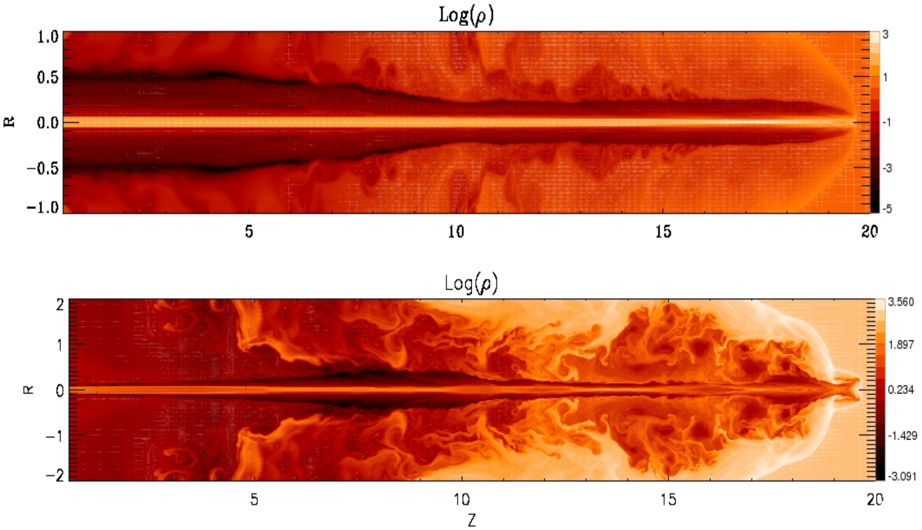
$\Rightarrow$ 10 model computations, **varying** $\Gamma_b = 10 - 20$ **and** $\theta = 0 - 1$

$\Rightarrow$ always CD, with/out ρ variation, Case II 10^{46} $ergs/s$ at $t = 900$



$\Rightarrow$ **FR II jet at first, then dramatic slowdown with FR I appearance**

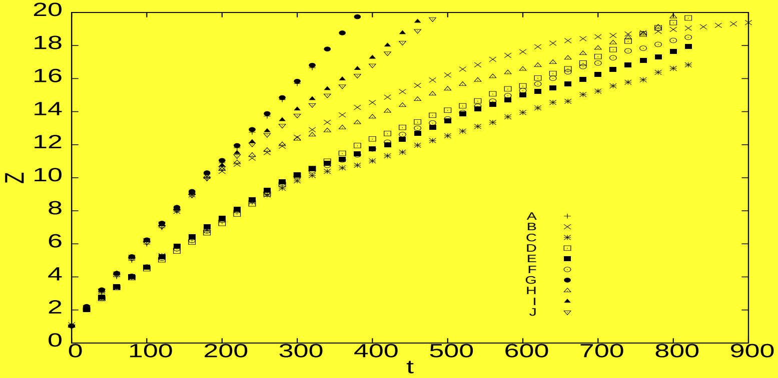
- high energy jets: need significant contrast to induce FR I transition



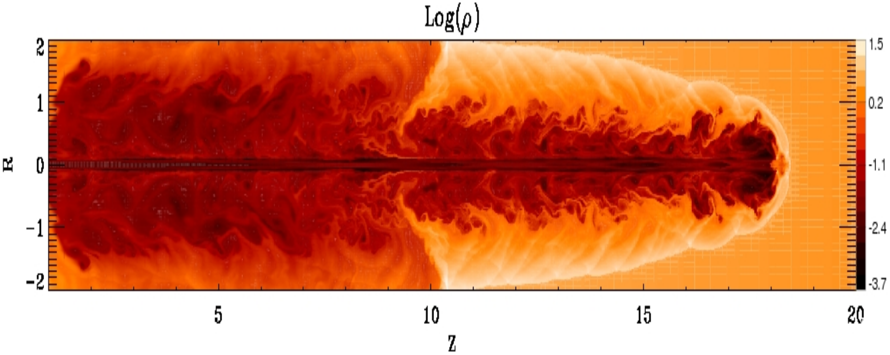
$\Rightarrow \Gamma = 10$, **density jump 10-1000**, IGM stratification effects

A&A 491, 321-337 (2008)

- overall findings on jet deceleration
  - ⇒ **FR II-FR I transition feasible at large density contrast**
  - ⇒ FR I changeover: relativistic at pc to subrelativistic at kpc



- FR I low energy jets: **Richtmeyer-Meshkov instability** as shock passes CD

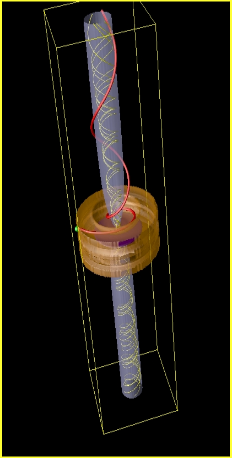


⇒ all **high-resolution, grid-adaptive computations, effective resolutions of** 3000×5000**, 4 to 6 refinement levels**

⇒ typical execution times: **4 days on 64 processors**

Internal stratification effects and jet deceleration

- AGN jets **radial stratification: fast inner, slow outer jet**
  $\Rightarrow$ different launch mechanism $\rightarrow$ different rotation
- **outer 'disk' jet launched magnetocentrifugally**
  $\Rightarrow$ Magnetized Accretion-Ejection Structure (MAES)



- generic mechanism for jet launch
  - $\Rightarrow$ magnetic torque brakes disk matter azimuthally
  - $\Rightarrow$ magnetic torque spins up jet matter
  - $\Rightarrow$ mass source for jet: disk
  - $\Rightarrow$ B collimates, accelerates
  - $\Rightarrow$ **Jet formation animation** & **Escaping accretion**
- accretor can be very different
  - $\Rightarrow$ YSO, compact object, AGN

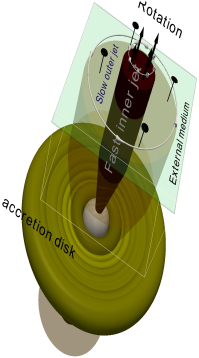
Two-component jet model

- **close to central engine: GR mechanisms launch additional inner jet**

  ⇒ efficient extraction AM from inner disk + black hole (Blandford-Znajek mechanism)

  ⇒ fast rotating inner jet, introduce **radially layered jet**

  ⇒ inner $\Gamma \sim 30$, outer $\Gamma \sim 3$

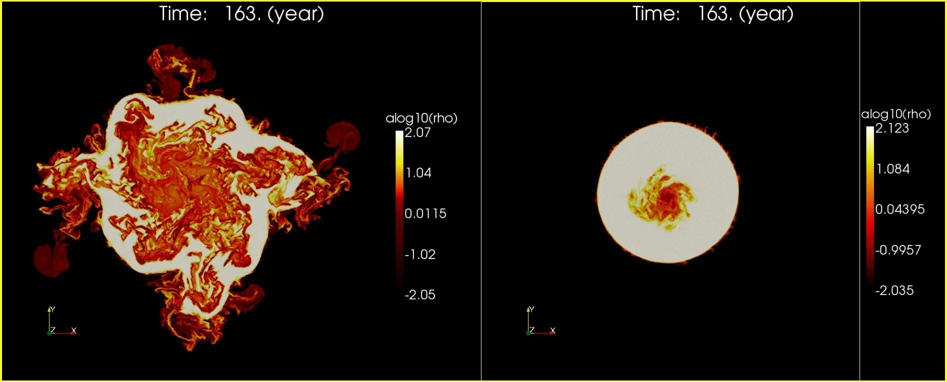


- perform 2.5D runs in cross-section
  - ⇒ variation along jet axis ignored
  - ⇒ both HD and MHD runs
  - ⇒ explore differences in effective inertia
- repeat in full 3D HD
  - ⇒ confirm & complement 2.5D scenario

Meliani & Keppens, ApJ 705, 1594-1606 (2009)

- vary relative contribution inner jet to total $L_{Jet,Kin} \sim 10^{46} ergs/s$

  $\Rightarrow$ discovery **new relativistic, centrifugal Rayleigh-Taylor mode**



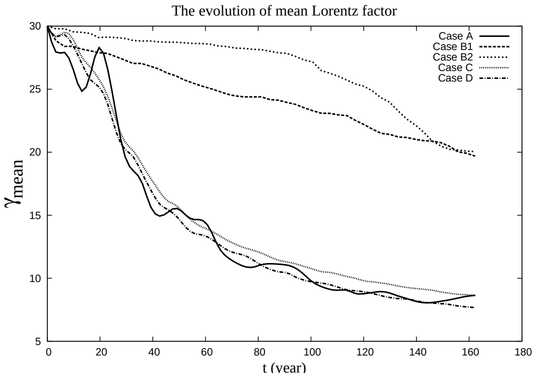
$\Rightarrow$ **FR I versus FR II related to launch efficiency inner jet!**

- novel **relativistically enhanced Rayleigh-Taylor mode**
  - $\Rightarrow$ approximate **dispersion relation**
  - $\Rightarrow$ insert spatio-temporal dependence $\exp(\lambda\, t - k \mid \zeta \mid)$ with displacement ζ

$$\lambda^2 \propto k \left[\left(\Gamma^2 \rho h + B_z^2 \right)_{in} - \left(\Gamma^2 \rho h + B_z^2 \right)_{out} \right]$$

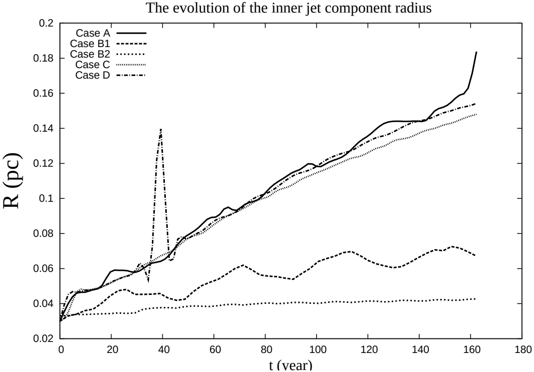
- **Stability: effective inertia outer jet $>$ effective inertia inner jet**
  - $\Rightarrow$ works for both HD and MHD relativistic jets
  - $\Rightarrow$ purely poloidal B effect incorporated
  - $\Rightarrow$ **No classical counterpart (relativistic flow essential)!**
  - $\Rightarrow$ $\Gamma^2 h$ effect with h specific enthalpy
  - $\Rightarrow$ **relativistic EOS crucial**: cold/hot outer/inner jet

- stable versus unstable jets: **design initial conditions with varying contribution of inner/outer jet to total kinetic energy flux**
  - $\Rightarrow$ criterion predicts cases A, C, D stable; B1, B2 unstable
  - $\Rightarrow$ **evolution of inner jet mean Lorentz factor**



$\Rightarrow$ efficient AM redistribution and enhanced inner/outer jet mixing when mode develops

- can quantify jet de-collimation due to mode development



$\Rightarrow$ non-axisymmetric mode development ultimately responsible

$\Rightarrow$ relativistic RT mode decelerates inner, decollimates total jet

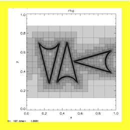
- **FR II/FR I transition thereby related to central engine**

$\Rightarrow$ depends on distribution kinetic energy over two-component jet

Outlook

- *In summary:* realistic relativistic (M)HD models
  - ⇒ external medium influence HYMORS: one-sided FR II to FR I
  - ⇒ radial jet stratification: FR II versus FR I
- **Related References:**
  - ⇒ Meliani & Keppens, A&A 475, 785 (2007)
  - ⇒ Meliani et al., A&A 491, 321 (2008)
  - ⇒ Keppens et al., A&A 486, 663 (2008) **A&A Highlight**
  - ⇒ helical B jets: magnetic reacceleration across cross-shocks
  - ⇒ Meliani & Keppens, ApJ 705, 1594 (2009)

Adaptive Mesh Refinement & AMRVAC



- extreme contrasts, positive p, ρ, τ, $v < 1$, $\Gamma \geq 1$, solenoidal B
  - $\Rightarrow$ stringent demands on numerics and accuracy: **AMR vital**
- **Special relativistic HD and MHD: 'modules' in AMRVAC**
  - $\Rightarrow$ *CPC* **179** 2008, 617, *JCP* **226** 2007, 925, *MNRAS* **376** 2007, 1189
  - $\Rightarrow$ advection, hydro, MHD, relativistic (M)HD modules
  - $\Rightarrow$ **different EOS implemented for relativistic modules**
  - $\Rightarrow$ any-D, explicit **grid adaptive framework**
  - $\Rightarrow$ **full MPI octree variant, cartesian/cylindrical/spherical**
- shock-capturing schemes (TVDLF/HLL/HLLC/Roe), reconstructions (linear/PPM)