Stability of relativistic two-component jets

Dimitrios Millas
28th Texas Symposium
16/12/2015, Geneva

Rony Keppens, CmPA, KU Leuven
Z. Meliani, LUTH, Observatoire de Paris - Meudon
Outline

• Why two-component jets?

• Previous work

• Jets with poloidal & toroidal magnetic field

• Summary

• Future work
Why two components? Observations!

- Indications: brightening, variability in TeV,…

- Variability in TeV:
  - high $\gamma$
  - ultra relativistic bulk motion of the jet

- Radio observations of pc-scale structure:
  - broad, slow (but relativistic) motion

- Two different (at least in terms of velocity) regions!

- Sometimes (?):
  - Fast, light inner jet
  - Slow, heavier outer jet
Examples

SEDs comparison for Cen A and Mkn 421 (Ghisellini et al. 2005)
Radio and x-ray observations of radio loud quasar PKS 1127-145
(Siemiginowska et al. 2007)
Previous work

MHD 2.5D simulations with MPI-AMRVAC

- Meliani & Keppens 2007: Relativistic HD
- Meliani & Keppens 2009: Relativistic MHD, poloidal magnetic field only

Aim:
Investigate non-axisymmetric instabilities, induced by differential rotation

Rayleigh criterion for rotational stability

- Rotation leads to centrifugal effects

- How to determine (in)stability?
  
  i. \( \frac{d(r^4 \Omega^2)}{dr} > 0 \) stable

  ii. \( \frac{d(r^4 \Omega^2)}{dr} < 0 \) unstable

  iii. \( \frac{d(r^4 \Omega^2)}{dr} = 0 \) marginally stable

- Relativistic equivalent: angular momentum flux must increase with \( r \)

\[
I = \gamma \frac{\rho + \frac{\Gamma}{\Gamma - 1} p}{\rho} \nu_\phi r - \frac{B_p}{\gamma \rho \nu_\rho} r B_\phi
\]
Stability:

- Momentum equation near equilibrium
  \[
  (\gamma^2 \rho h + B_z^2)(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla)\vec{v} + \nabla P_{tot} + \vec{v} \frac{\partial P_{tot}}{\partial t} + \cdots = 0
  \]

- Ignore lab frame contribution to charge separation (valid far inside the light cylinder)

- Assume perturbation is potential, plane wave
  \[
  \lambda^2 \sim k[(\gamma^2 \rho h + B_z^2)_{in} - (\gamma^2 \rho h + B_z^2)_{out}]
  \]

Stability: \( \lambda^2 < 0 \) thus \( (\gamma^2 \rho h + B_z^2)_{in} < (\gamma^2 \rho h + B_z^2)_{out} \)
Initial velocity profile

- \( V_z(r) = \begin{cases} \gamma_{z,in} \approx 30, & r \leq r_{in} \\ \gamma_{z,out} \approx 3, & r > r_{in} \end{cases} \)

- \( V_\varphi(r) = \begin{cases} v_{\varphi,in} \left( \frac{r}{r_{in}} \right)^{a_{in}/2}, & r \leq r_{in} \\ v_{\varphi,out} \left( \frac{r}{r_{in}} \right)^{a_{out}/2}, & r > r_{in} \end{cases} \)

\[ \frac{d(r^4\Omega^2)}{dr} > 0 \text{ stable} \]
\[ \frac{d(r^4\Omega^2)}{dr} = 0 \text{ marginally stable} \]

\[ \frac{d|I|}{dr} \propto (1 + \frac{a}{2}) \]

- Interface is unstable!
Constraints from observations:

- **Radius of outer jet**: $R_{\text{out}} = 0.1$ pc
  - Radio observations of M87, Biretta et al. 2002

- **Inner radius less constrained**: $R_{\text{in}} = R_{\text{out}} / 3$

- **Kinetic luminosity flux**: $L = 10^{46}$ erg/s
  - Typical for radio loud galaxy

- **Initial density profile**: constrained by kinetic energy flux
  - Assume that inner jet carries $<1\%$ of total kinetic energy flux
• Initial Lorentz factor: typical values for AGN jets
  - $\gamma_{z,\text{in}} \approx 30$
  - $\gamma_{z,\text{out}} \approx 3$

\[ \rho(r) = \begin{cases} 
6.92 \rho_{\text{ext}}, & r \leq r_{\text{in}} \\
119.94 \cdot 10^3 \rho_{\text{ext}}, & r_{\text{in}} < r < r_{\text{out}} \\
\rho_{\text{ext}}, & r > r_{\text{out}} 
\end{cases} \]

• Total pressure balanced at each interface

• External medium density: used for scaling only
Initial magnetic field profiles

\[ B_\phi (r) = \begin{cases} 
B_{\phi, in} \left( \frac{r}{r_{in}} \right)^{a_{in}/2}, & r \leq r_{in} \\
B_{\phi, out} \left( \frac{r}{r_{in}} \right)^{a_{out}/2}, & r > r_{in}
\end{cases} \]

\[ B_z (r) = \begin{cases} 
\sqrt{0.01 \gamma_{in}^2 \rho_{in}}, & r \leq r_{in} \\
0, & r > r_{in}
\end{cases} \]

\[ \sigma = 0 \rightarrow \text{kinetically dominated jet} \]
(magnetization: \( \sigma \equiv \text{poynting to mass flux ratio} \))
\( \gamma_{in} \sim 30 \)
\( v_{\phi in} \sim 0.01 \)
\( B_p \) field
\( \gamma_{out} \sim 3 \)
\( v_{\phi out} \sim 0.1 \cdot v_{\phi in} \)
\( 10^5 \rho_m \)
\( 6.92 \rho_m \)

external region (static)
Proper density at 0.5, 1 and 2.5 rotations of the inner jet
Output from the simulations

• Inner jet & shear region end up magnetized

• Inner jet decelerates a little ($\gamma \sim 20$)

• Components remain separable in inner and outer jet

• Inner jet displaced from on-axis due to non axisymmetric modes

• Stratification converges to:
  • Inner fast, magnetized spine with $\gamma \sim 20$
  • Shear shell 100 times denser, lower $\gamma$
• Effective inertia important for the evolution!

\[ \gamma^2 \rho h + B_z^2 \]

• Why?
  – Dispersion relation depends on the difference between the eff. inertia of inner & outer jet!

• Purely poloidal field case: \( \gamma^2 \rho h|_{\text{out}} \approx 3.2[\gamma^2 \rho h + B_z^2]|_{\text{in}} \)

• Different evolution for \( \gamma^2 \rho h|_{\text{out}} \approx 18[\gamma^2 \rho h + B_z^2]|_{\text{in}} \)
  (see Meliani & Keppens 2009)
Jets with toroidal magnetic field
\[ B_{\phi}(r) = \begin{cases} 
B_{\phi,\text{in}} \left( \frac{r}{r_{\text{in}}} \right)^{a_{\text{in}}/2} , & r \leq r_{\text{in}} \\
0 , & r > r_{\text{in}} 
\end{cases} \]

\[ B_z(r) = \begin{cases} 
B_{\text{zin}} , & r \leq r_{\text{in}} \\
\sqrt{0.001\gamma_{\text{out}}^2 \rho_{\text{out}}}, & r > r_{\text{in}} 
\end{cases} \]

- Select \( B_{\phi} \) that corresponds to \( \sigma = 10^{-3} \)
- Use I criterion to determine \( B_z \) of inner jet
- \( B_z \) of outer jet not explicitly constrained (\( \sim 3B_{\text{zin}} \))
- Density contrast same as in previous cases
Proper density at $t = 0$
Proper density after half rotation of the inner jet
Proper density after one full rotation of the inner jet
Proper density after 1.5 rotations of the inner jet
\( B\phi = 0 \)

\( B\phi \neq 0 \)

Average Lorentz factor of the inner jet with time (in rotations of inner jet)
(Preliminary) Results

- Case with zero toroidal field seems to agree with Meliani & Keppens, 2009
  - Rayleigh-Taylor type instabilities

- Including low $\sigma$ toroidal field does not stabilize the system

- Eff.inertia ratio out/in $\sim 0.1$

- Formation of shear region, deceleration of the jet (up to $\sim 1$ rotation)

- Applications in FRI / FRII possible with proper adjustment
Future Work & Work in progress

- Examine $B_\phi$ connection with I criterion, new modes etc.
- High resolution runs (now 2 AMR levels, 200x200 base resolution)
- Analyze other jet parameters (e.g. radius with time)
- Examine different effective inertia ratios
  - Difference between FRI & FRII?
- More realistic configurations for $B_\phi$ and (mainly) $v_\phi$
  - Avoid steep transition
- Validate results:
  - create virtual radio maps & compare with observations
- Later on: 3D simulations
  - Different magnetization regimes (Poynting / kinetically dominated jets)
  - Other types of instabilities must be considered (e.g. Kink)