HOT SELF-SIMILAR RELATIVISTIC MHD FLOWS

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ABSTRACT

We consider

- self-similar axisymmetric relativistic jets
- with toroidal magnetic field
- ultrarelativistic equation of state

Zakamska, Begelman, Blandford 2008, ApJ, 679, 990

One of the solutions: parabolic jet. Its structure:

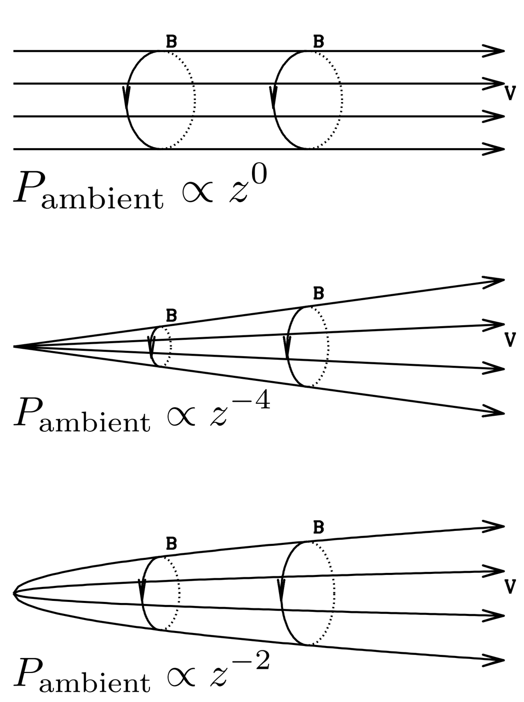
- either pile-up of material due to internal pressure gradients
- or magnetic pinch along the axis

Emissivity pattern of the jet and projection effects have strong effects on observed synchrotron emission and polarization - even for purely toroidal magnetic field.

- Edge-brightened jets (e.g., M87) - possible evidence of pile-up
- Polarization fraction rises to the edge (e.g., Mrk501) in jets with a magnetic pinch
- Geometric projection leads to the ``spine-sheath" polarization pattern.

MODEL

- We assume: relativistic; pressure dynamically important; purely toroidal B-field; purely poloidal velocity
- We look for self-similar solutions (streamlines $z \propto r^k$)
- Cylindrical, conical and parabolic solutions
- With these assumptions, equations of ideal MHD in special relativity turn into a force equation for every cross-section of the jet
- Boundary conditions: pressure equilibrium with ambient medium



Euler equation for the cross-section:

- Cylindrical or conical jet:
Radial pressure gradients+magnetic tension (or magnetic pinch)=0

- Parabolic jet:
Pressure gradients+magnetic tension=centripetal force (to provide the curvature of streamlines)

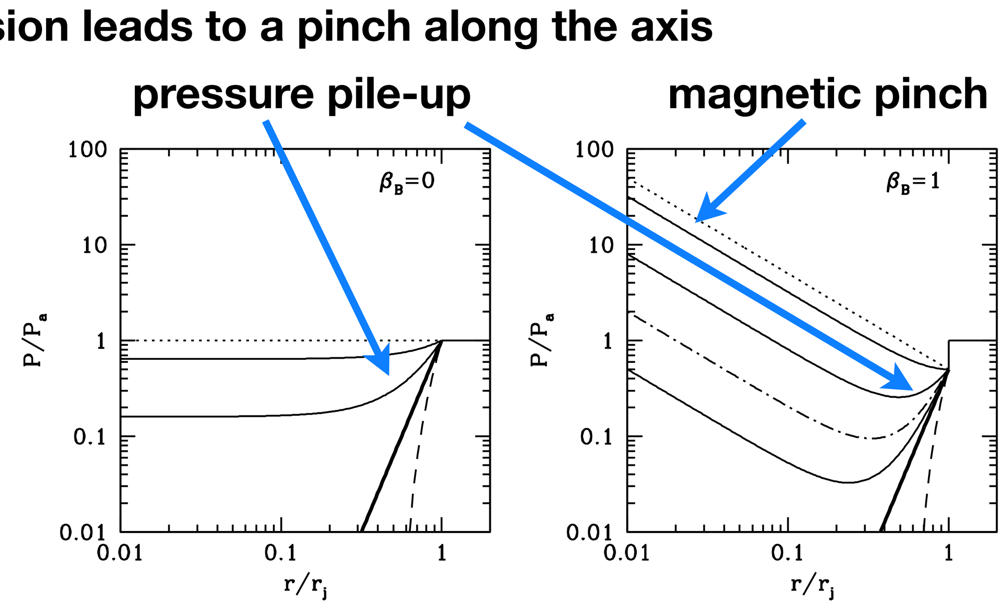
SOLUTIONS

Lateral pressure profiles of parabolic jets in our model:

- Pressure gradients lead to pile-up at the edge;
- Magnetic tension leads to a pinch along the axis

Parameters that control the structure:

- Magnetization
$\beta_B = B^2/8\pi P\gamma^2$
- Lorentz-factor (or total energy of the jet)

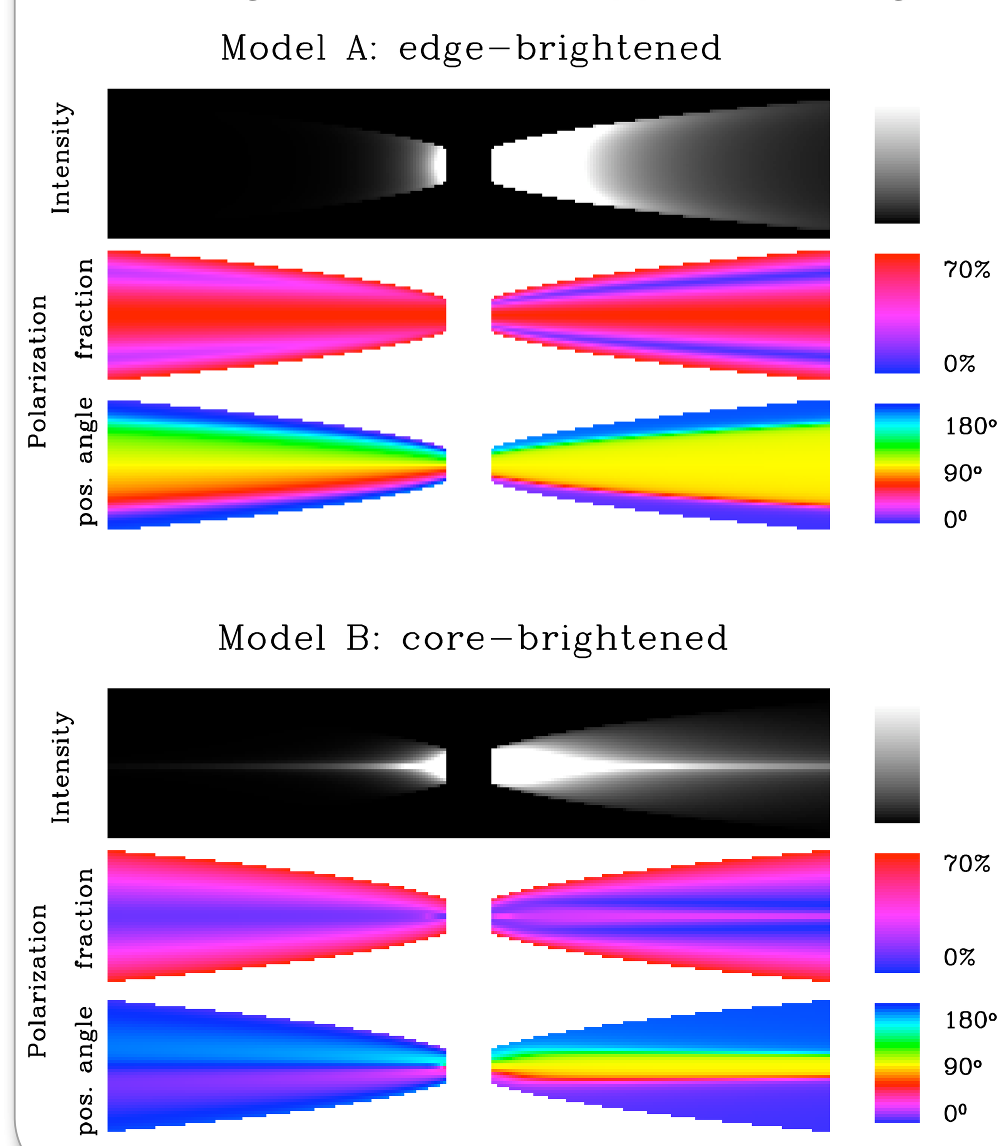


Left panel: non-magnetized jet; right panel: magnetized jet.

- In each panel, different lines, from top to bottom, are solutions for the lateral pressure profile of the jet with increasing Lorentz-factor.
- Dotted lines: solutions for cylindrical jet (when magnetization alone determines pressure profile)
- Thick solid lines: the highest Lorentz-factor solution.
- Pressure-matched solutions do not exist for $\gamma \geq 1/\theta$, where θ is the opening angle of the jet. For higher γ, streamlines on the edge lose causal contact with streamlines near the axis.

MODELS OF EMISSION

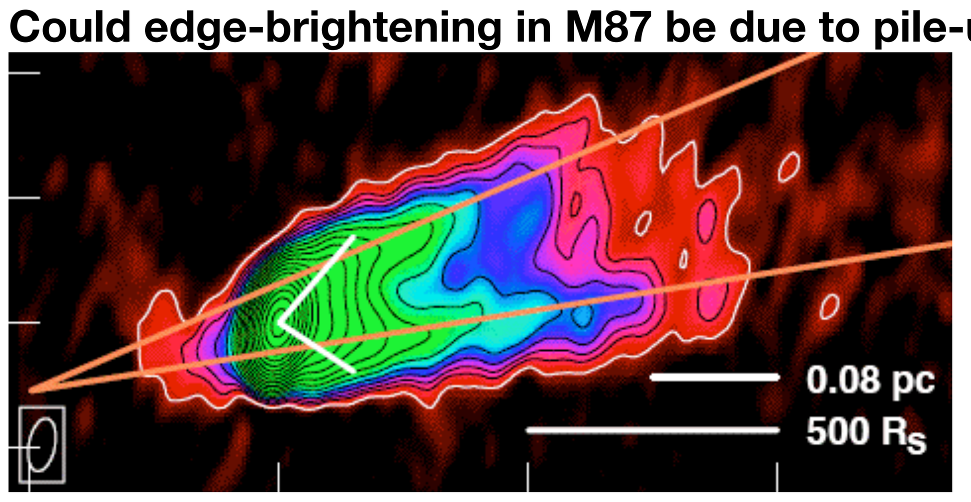
- We assume optically thin synchrotron
- Pressure, magnetic field from our models yield emissivity per unit volume
- We integrate along multiple lines of sight to produce maps of synchrotron intensity and Stokes parameters
- Taking into account Doppler boosting and relativistic aberration



- Both examples have the same magnetization
- Model A is dominated by pile-up (high Lorentz-factor)
- Model B is dominated by the magnetic pinch (low Lorentz-factor)
- The axis of the jet is inclined at 30 degrees to the line of sight (right-hand side is moving toward the observer)
- Core region is excluded from the map
- Orientation of E-field of polarization: blue - perpendicular to the axis; yellow - parallel to the axis

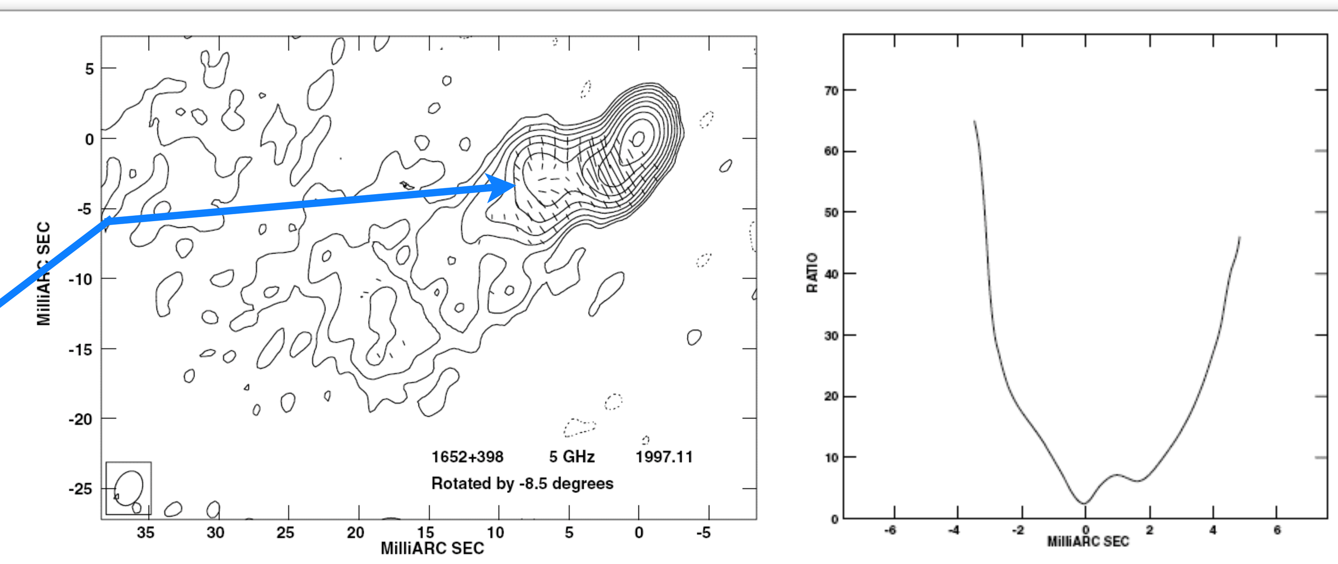
OBSERVATIONAL IMPLICATIONS

Could edge-brightening in M87 be due to pile-up?



- M87 - observed in the collimation region
- Shape is close to parabolic
- Can use our model to estimate total jet energy (a few $\times 10^{44}$ erg/s)

Radio map of M87 jet from Ly, Walker, Junor 2007, ApJ, 660, 200



Radio map of Mrk501 and polarization fraction across the jet from Pushkarev et al. 2005, MNRAS, 356, 859

Properties of polarization in our models:

- Near the edge of the jet, orientation of polarization is perpendicular to the axis (because toroidal B in projection is parallel to the axis in these points)
- Near the axis, polarization is parallel to the axis
- This is the puzzling ``spine-sheath" polarization pattern observed in some BL Lac objects (usually interpreted as a change in B-field orientation)
- But it can be accounted for by a purely toroidal field and geometric projection effects

In jets dominated by a magnetic pinch (model B):

- Polarization near the axis is low because of superposition of emission from regions with different directions of B; polarization near the edge is high
- This polarization pattern is observed in some jets (Mrk501, Pushkarev et al. 2005; 3C273, Zavala and Taylor, 2005)

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