VLBA & Chandra Observations of UGC FRI radio galaxies: Constraints on Jet Evolution

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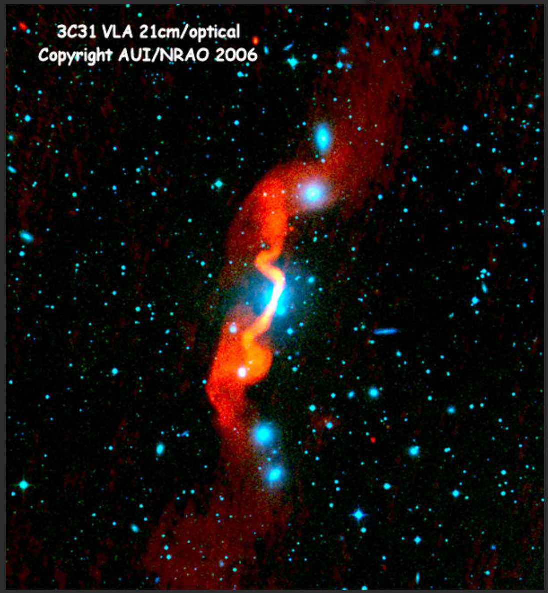
Radio Galaxy Sample



✧ Complete sample of 21 nearby (*z < 0.023*) Fanaroff-Riley type I radio galaxies from the Uppsala General Catalog

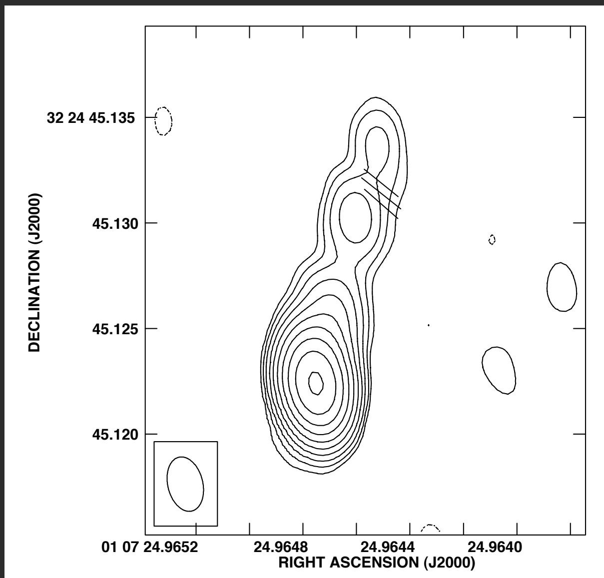
✧ *Multiwavelength campaign: Verdoes Kleijn et al. (1999, 2002, HST/WFPC2); Noel-Storr et al. (2003, HST/STIS); Xu et al. (2000, 1.6 GHz VLBA-VLA)*

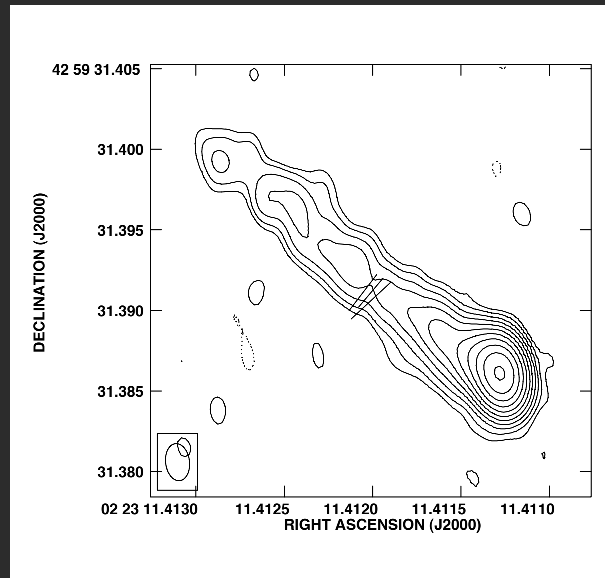
✧ 10 of 21 showed parsec-scale core-jet structures

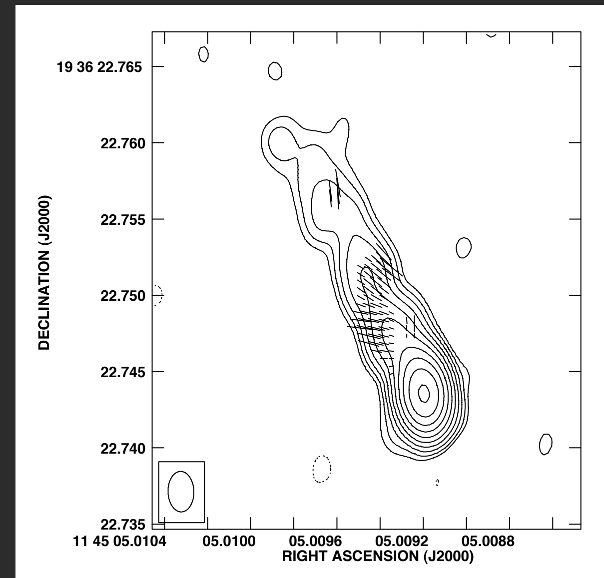
These 10 observed with polarization sensitive VLBA at 5 GHz

(Kharb et al., 2012, submitted to ApJ)

VLBA Polarimetry







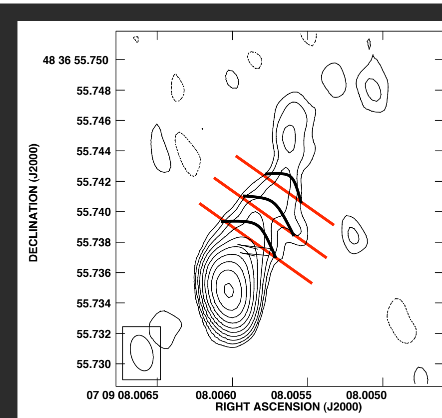
✧ 7 of 10 show polarized emission in jet; m_{jet} ~ 5% - 30%
"Spine – sheath" structure --- Jet-medium interaction or Helical magnetic field

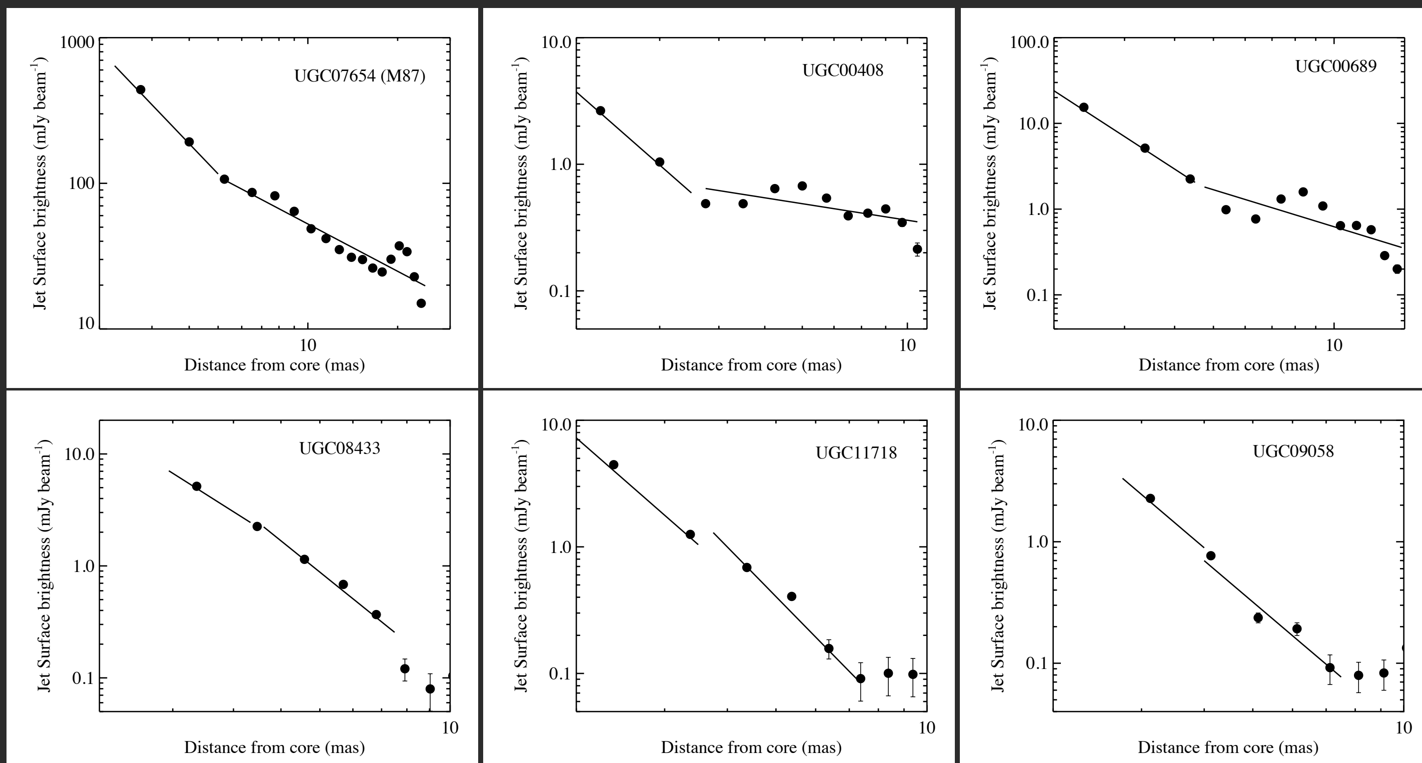
✧ At 5 GHz, RM ≈220 rad m^{-2} required to rotate χ by 45° --- *Observed* in FRI jets (e.g., *Taylor et al. 2001; Kharb et al. 2009*)

✧ Jet sheath with path length = 10% of jet width (~5 pc), electron density ~0.1 cm^{-3} (hot X-ray gas in ellipticals; *Mathews & Brighenti, 2003*), "equipartition" B field ~5 mG

"Mixing layer" between jet and surrounding medium - threaded by a helical magnetic field (?)

Jet Intensity Evolution on Parsec-scales





✧ 7 jets have $\log(I_\nu)$ vs. $\log(d)$ slopes ≈ -1.5

✧ 3 jets have slopes ≈ -3.5

Adiabatic Expansion: Relativistic Jet

$$I_\nu \propto (\Gamma_j v_j)^{-(\gamma+2)/3} r_j^{-(5\gamma+4)/3} D^{2+\alpha}$$

B_{pol} -dominated region

$$I_\nu \propto (\Gamma_j v_j)^{-(5\gamma+7)/6} r_j^{-(7\gamma+5)/6} D^{2+\alpha}$$

B_{tor} -dominated region

(*Baum et al., 1997, ApJ*)

$\gamma = 2\alpha + 1$; $D = 1/[\Gamma(1-\beta\cos\theta)]$; $\beta = v_j/c$; $\Gamma = 1/\sqrt{(1-\beta^2)}$

Case-I

- For a jet with constant velocity on parsec-scales and $\alpha = 0.7$ ($\gamma = 2.4$)
  $I_\nu \sim r_j^{-5.3}$ B_{pol} **$I_\nu \sim r_j^{-3.6}$** B_{tor}
- If $r_j \sim d^p$, then p ~ 0.3 - 0.4 for the sources with slopes ≈ -1.5
- $r_j \sim d^{0.4}$ – gradual jet expansion which we cannot observe with our data.
  Need higher resolution observations, e.g., 15 GHz

Case-II

✧ For a jet with constant radius on parsec-scales and $\alpha = 0.7$ ($\gamma = 2.4$)

$$I_\nu \sim (\Gamma v_j)^{-1.5} D^{2.7} \quad B_{pol}$$

$$I_\nu \sim (\Gamma v_j)^{-3.2} D^{2.7} \quad B_{tor}$$

✧ If $v_j \sim d^q$, then slopes match observations for jet distances = 0.5 – 3.5 pc
$\theta \sim 15° – 25°$ for B_{tor}, $\theta \sim 30° – 50°$ for B_{pol}, $\beta = 0.9 – 0.6$
$q = 0.05 – 0.23$ ➔ ***Accelerating jet !***

✧ Acceleration on parsec-scales ➔ "Magnetic driving" in highly magnetized jets (*e.g., Vlahakis & Konigl, 2004, ApJ*)

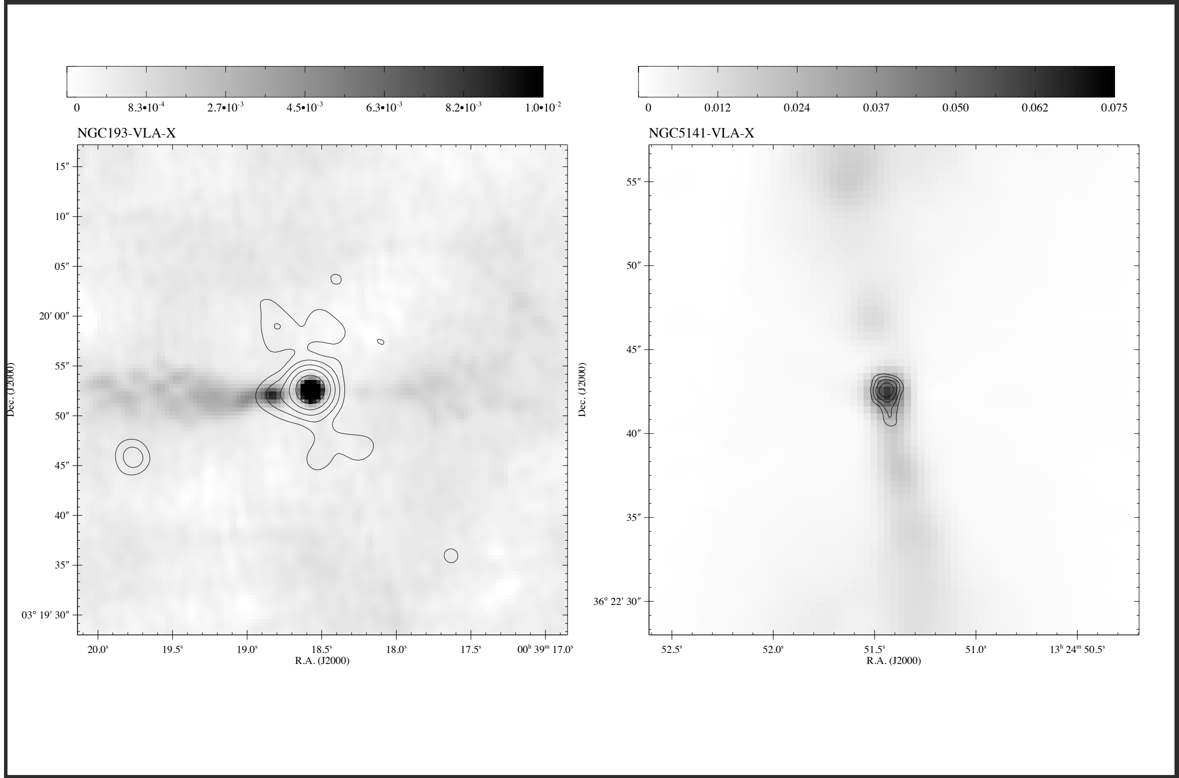
✧ *Pro*: VLBI monitoring reveals accelerating jet knots (*e.g., Cotton et al. 1999*)

✧ *Con*: Jet speed exceeds speed of light beyond ~4 pc!

✧ Case I is favored – jets expand gradually but unobservable at 5 GHz

✧ 3 sources with slopes ≈ -3.5, may have high jet Lorentz factors - Doppler dimming - faster fall in Intensity with distance

Chandra Observations of UGC FRI sample



✧ 9/15 (~60%) sources observed with *Chandra X-ray Observatory* reveal X-ray jets

Radio = Grey-scale
X-ray = Contours

✧ X-rays in FRIs are synchrotron emission (*e.g., Worrall 2009, A&A Rev.*)

✧ Need particle re-acceleration

✧ Sites of bulk jet deceleration

✧ Scales ~ few kpc

Summary

- ✧ VLBP @ 5 GHz of 10 FRI radio galaxies from a complete sample of 21 UGC FRIs reveals polarized emission in 7 ➔ presence of highly ordered magnetic fields on parsec scales.
- ✧ Aligned magnetic fields at jet edges – "sheath"; Bimodal magnetic field structures – "spine-sheath" ➔ Jet-medium interaction or Helical magnetic fields.
- ✧ Can explain the oblique polarization as coming from a "sheath" which is a "mixing" layer. This outer layer could be threaded by a helical magnetic field.
- ✧ Intensity evolution suggests that *if jets expand adiabatically* then (1) jet expansion is gradual and unobservable in 5 GHz VLBI images, or (2) the jet is accelerating on parsec-scales. Case I favored.
- ✧ 9 out of 15 FRIs show X-ray jets ➔ sites of bulk deceleration and particle re-acceleration.
- ✧ FRI jets start out relativistically on parsec-scales, but decelerate on kpc-scales.