Jets Lecture 5

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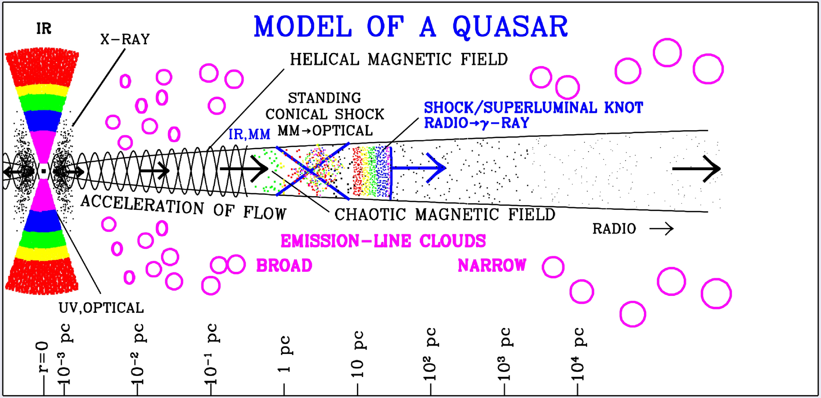
Outline

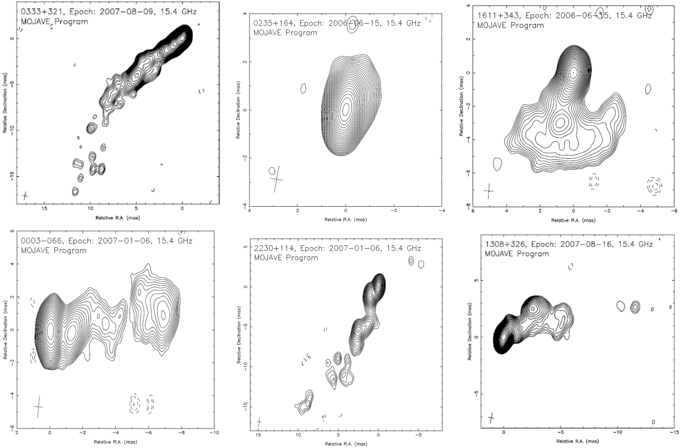
Observed structures in jets

AGN jet anatomy

Credit A. Marscher

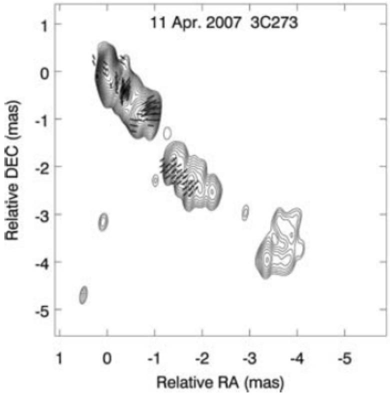


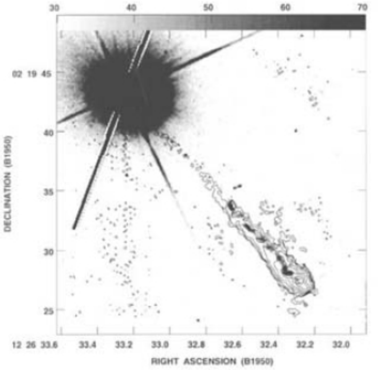
Observed structures in parsec scales



Morphologies include e.g., straight, long, short, broad, narrow, bent, wiggled, and knotty jets. Blazar jets are almost always one-sided and there is a bright point at one end of the jet, the “core”.

...and in kiloparsec scales





Example of quasar 3C273 in pc (43 GHz VLBA; left) and kpc (1.7 GHz VLA + HST optical; right) scales. The core in the pc-scale jet is very close to the over-exposed optical point source on the right-hand image. The scale difference between the images is ~ 4000. [From Marscher (2010)].

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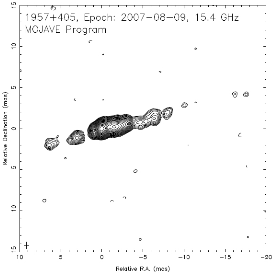

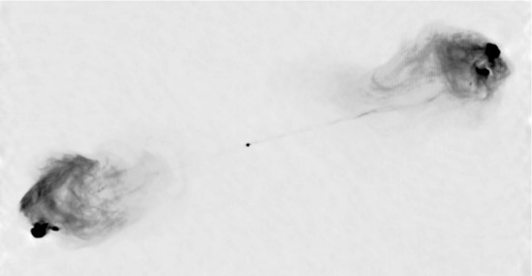

Example of an FR-II radio galaxy Cyg A in pc (15 GHz VLBA; left) and kpc (5 GHz VLA; right) scales. The pc-scale jet in left-hand image is located in the point-like core of the right-hand image. (Images: MOJAVE Survey and NRAO/AUI)

AGN jets in different scales

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- $r \gtrsim 1\,\mathrm{kpc}$ ($\gtrsim 10^8 R_g$): "kpc-scale jet": interaction between the jet and ambient medium

Models for the core: $\tau = 1$ surface in ultracompact self-absorbed jet

- Assume a steady-state conical jet of opening angle ϕ and with magnetic field strength and relativistic particle density decreasing with the jet cross-sectional radius R as: $B = B_0(R/R_0)^{-b}$ and $N = N_0(R/R_0)^{-n}\gamma^{-p}$. R_0 is the radius at the location where the emission turns on. (Blandford & Königl (1979) jet model)

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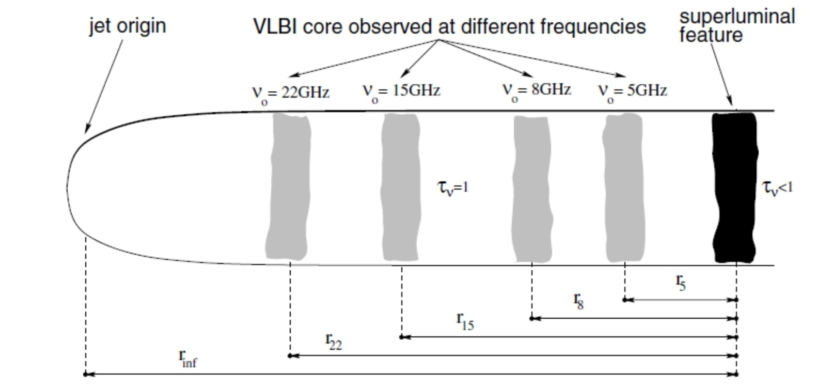
- Parameter $k_r = 1$ for pure synchrotron self-absorption and equipartition B-field strength. Indeed, observations give $k_r \approx 1$. Core shift allows another way to measure magnetic field strengths in jets.

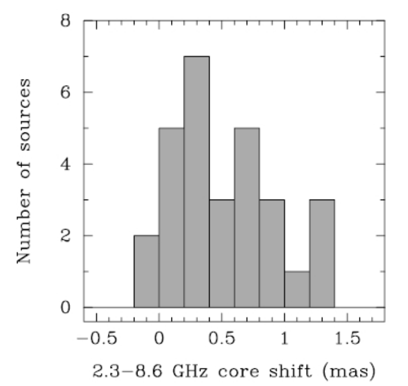
Core shift

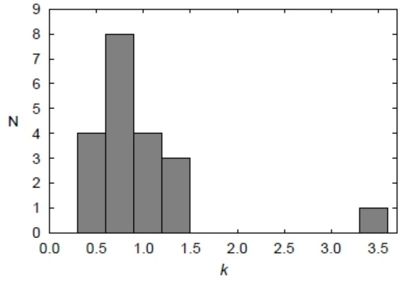
Lobanov (1996)



Core shift - measurements

Kovalev et al. (2008)





Sokolovski et al. (2011)

Models for the core: recollimation shock(s)

- Below about 20 GHz, the core is a $\tau = 1$ surface of the jet. But jets are not self-similar all the way down to the central engine, since their spectrum ceases to be flat typically somewhere between 50 and 500 GHz. So, could the "core" in the highest frequency VLBI maps be some physical feature?
- Series of recollimation shocks naturally arise in overpressured jets and are characterised by a local increase in pressure, density and B-field. First of such features in the optically thin part of the jet could be the "core" in the high-ν VLBI images.

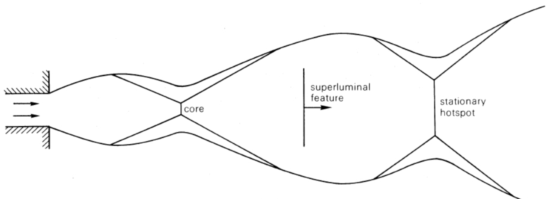


FIG. 4b

Daly & Marscher (1988)

Moving features – relativistic shocks

- A shock wave is produced by a disturbance moving faster with respect to the medium than its sound speed
- Relativistic shocks in jets can result from changes in the jet velocity or injected energy near the base of the jet
- A major disturbance is needed to generate a shock in a relativistic flow since the relative velocity needs to be supersonic (and sound speed in fully relativistic plasma is $c/\sqrt{3}$)
- In a shock wave pressure, density, velocity, and temperature jump almost instantly
- The bright moving "knots" seen in the VLBI images are likely relativistic shocks. Their ejection from the core is connected to flaring behaviour in these sources.

Significance of shocks in energy dissipation

- A shock front compresses the plasma, increasing its density by a factor of k across the shock front (so-called compression factor). k has a maximum of 4 in thermal plasma, but can be higher in relativistic plasma. However, $k \lesssim 2$ is typically expected.

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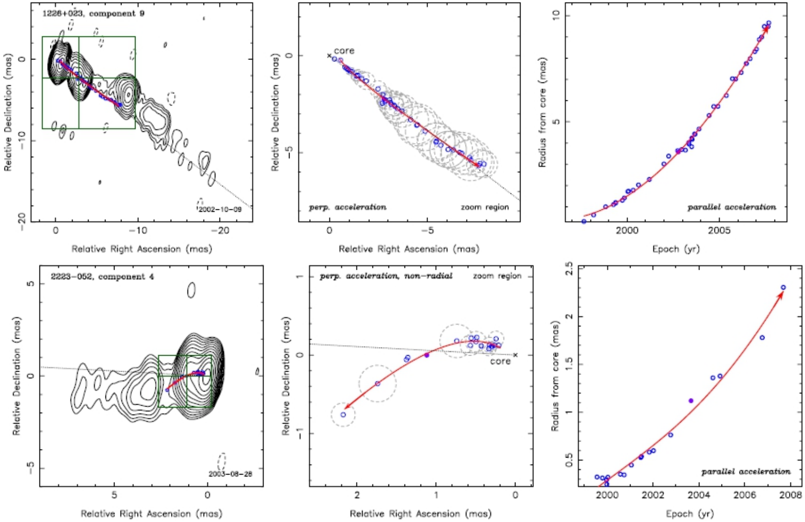
- If shocks indeed work as effective particle accelerators, they can tap the kinetic energy of the bulk flow and efficiently dissipate it.

Non-linear motions in parsec scale jet

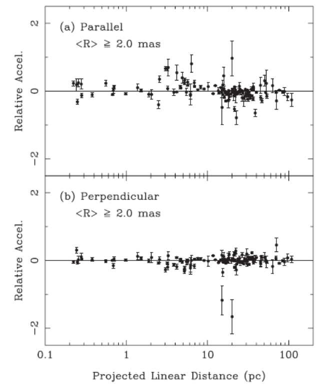
Homan et al. 2009



Non-linear motions in parsec scale jet

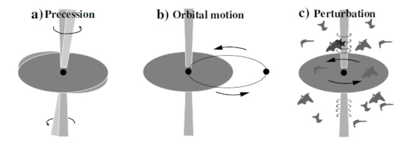
- About 1/3 of the moving features measured in MOJAVE survey show accelerations → These are not ballistic flows.
- A statistical argument can be constructed to show that since apparent parallel accelerations are typically larger than perpendicular accelerations, many of these features show intrinsic changes in their speed
- Parallel accelerations are typically positive close to the base of the jet → The jet flow is still accelerating in the parsec scales?

Homan et al. (2009)



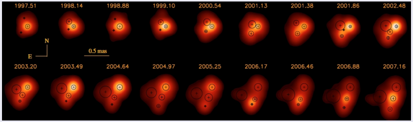
Changing jet direction

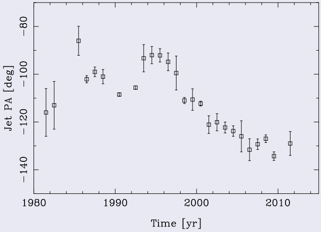
- Changes in the jet direction in parsec-scales are rather common: many jets "wobble"
- Precession of the disk-jet system, gravitational perturbation from a binary companion or (M)HD instabilities?



Credit: I. Agudo

Swing in NRAO150; Agudo et al. (2007)

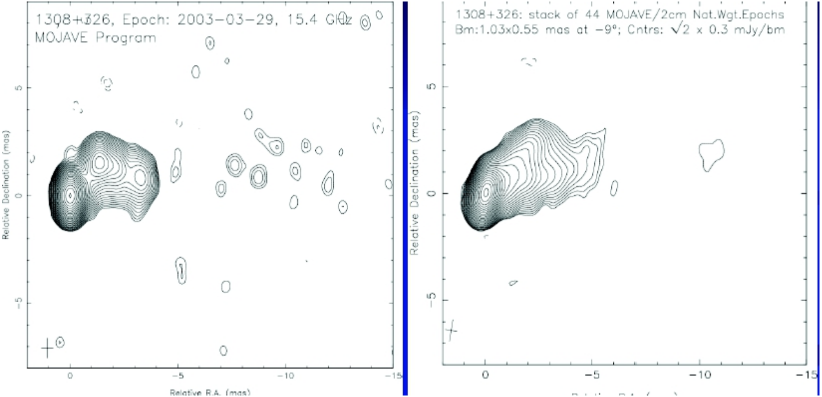




Historical pc-scale jet PA in OJ287

Changing jet direction – stacked images

Lister et al. 2009

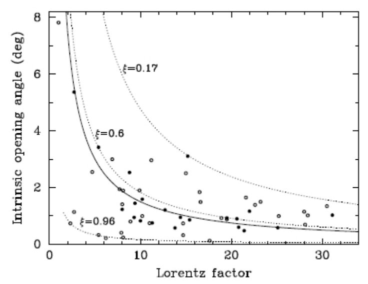


It also possible that the observed part of the jet does not represent the whole flow channel width

Jet opening angles

- Apparent jet opening angles are larger than the true jet opening angles due to projection effects

Pushkarev et al. (2009)



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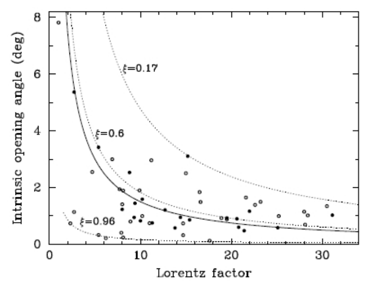

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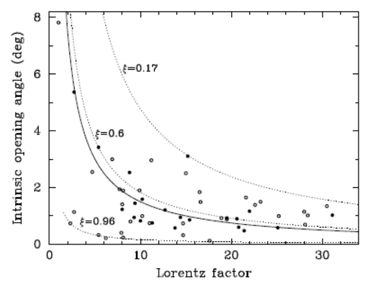
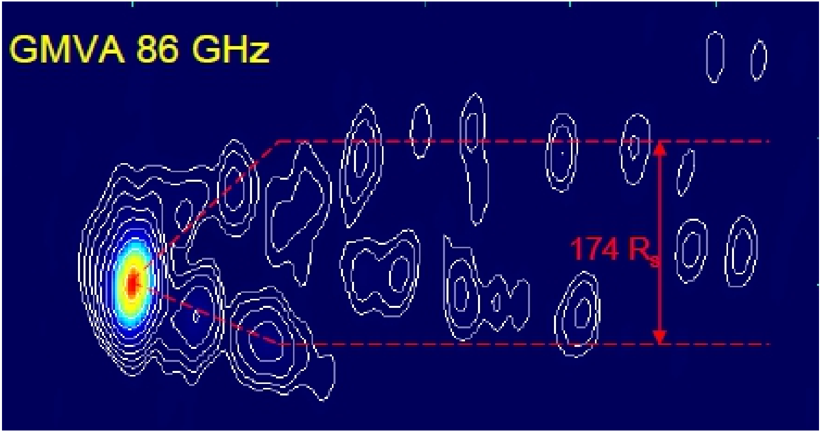
- The opening angles seem to be inversely proporional to the jet Lorentz factor. This relation may be due to extended acceleration of the flow: 1) in hydrodynamic acceleration the opening angle is inversely proportional to Mach number and 2) in magnetic acceleration, the collimation increases due to magnetic hoop stress.

Pushkarev et al. (2009)



Jet opening angle in M87: collimation in action?

Credit: T. Krichbaum



Instabilities: Kelvin-Helmholtz

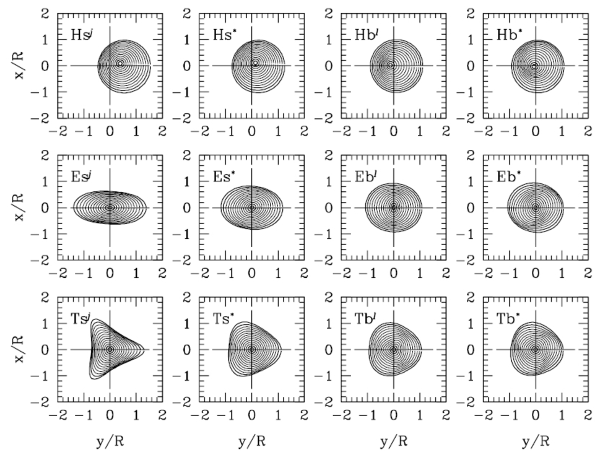
NOAA

K-H instabilities occur when two fluids have different velocities adjacent to a tangential discontinuity

- Jets are likely subject to Kelvin-Helmholtz instabilities
- Can be studied by performing linear perturbation analysis of the dispersion relation of the excited waves
- Surface modes: generate turbulence and velocity shear at the boundaries. Helical $m = 1$ surface mode can also displace the whole jet cross-section.
- Body modes: cause departure of cross-sectional geometry from circular symmetry
- K-H instabilities are capable of producing wavelike helical structures seen in the jets
- High Mach numbers, Lorentz factors and strong axial B-field stabilize the jet against K-H instabilities

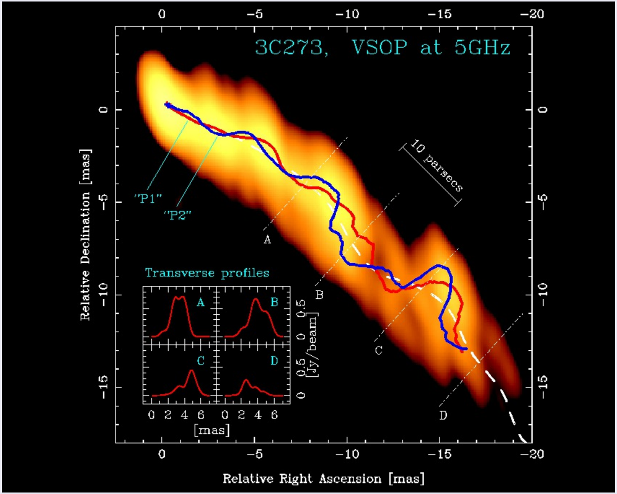
K-H modes

Hardee (2000)



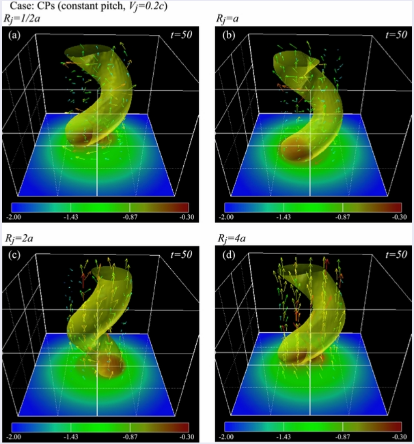
Example: Double-helix in 3C 273

Lobanov & Zensus 2001, Science



Instabilities: current driven

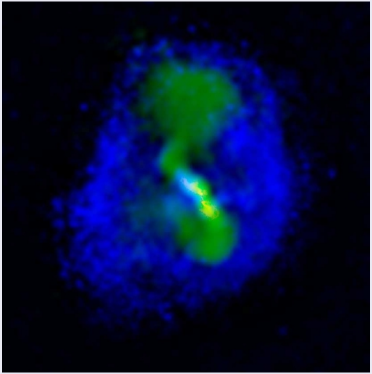
Mizuno et al. (2011)



- If energy in the toroidal B-field component is larger than the kinetic energy of the flow, the jet can become magnetically unstable
- Pinch mode creates a "sausage-like" jet
- Current-driven kink mode excites large scale helical motions that can even disrupt the system

Large scale structure – interaction with ambient medium

X-rays (blue) and radio (green) in Hydra A; Wise et al. (2006)



- In kpc-scales interaction of jet with ambient medium is important
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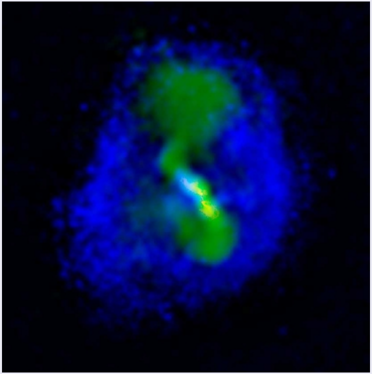

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- X-ray images of hot cluster gas show "cavities" formed by kpc-scale radio jets that have pushed away the intracluster medium. The work done in displacing volume of V of cluster gas at pressure p is pV and the energy of material inside is $pV/(\gamma - 1)$. X-ray images give p.

Magnetic field in jets

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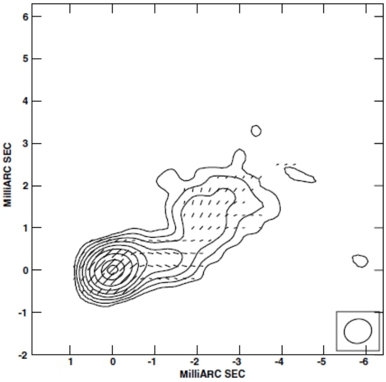
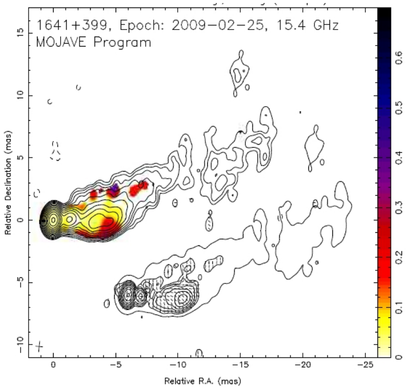
- Another possible explanation for low levels of linear polarization is so-called "Faraday depolarization"
- Also, for the optically thick core, there is a reduction in the maximum Π by a factor of ~ 7 due to self-absorption

Observed B-field structures

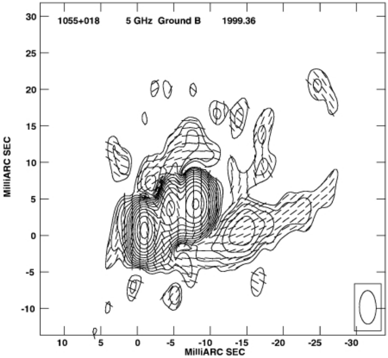


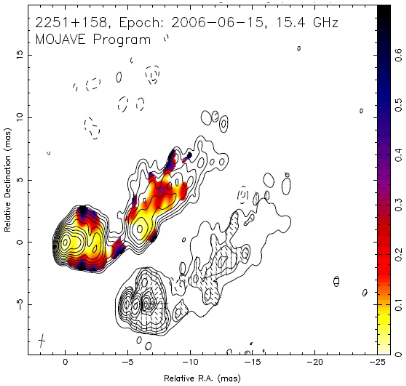


In BL Lacs the EVPAs follow curved jet trajectory → predominantly transverse magnetic field structure. Toroidal field or compression due to a series of shocks? In quasars, the pol. structures are more complicated (longitudal B-field + oblique shocks? jet-cloud interaction?)

(Image credits: D. Gabuzda and MOJAVE team)

Observed B-field structures



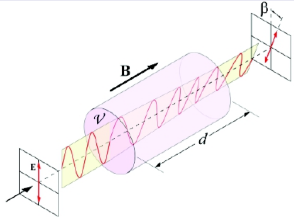


Spine-sheath structures, shock-structures ...

(Image credits: A. Pushkarev and MOJAVE team)

Birefringence effects – Faraday rotation

- Polarized em-wave traveling through magnetized $e^- - p^+$ plasma with thermal or low-γ electrons experiences "birefringence" effects
- Linearly polarized plane wave can be presented as sum of two opposite circularly polarized propagation modes. In birefringed medium these have different refractive indeces and different phase velocities. This causes the direction of linear polarization to rotate as the emission passes through this "Faraday screen".
- The amount of rotation is: $\Delta\chi = \frac{e^3\lambda^2}{2\pi m^2 c^4} \int n_e B_{||} dl = RM\lambda^2$, where l is a path length through the screen and B is the magnetic field component along the line of sight in the screen. Electron density $n_e = n_e^{thermal} + n_e^{\gamma}/\langle\gamma\rangle$.

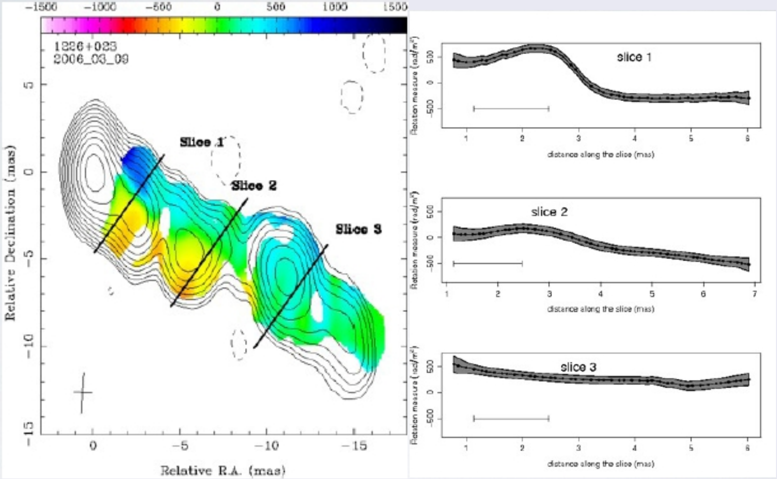


RM is called the "rotation measure" and it can be measured from multi-wavelength polarization observations.

Helical fields in parsec scales?

- Faraday rotation can take place in the emission source itself or in an external screen
- Intrinsic FR or FR in a "sheath" of a jet can give a possibility to measure the line-of-sight component of jet B-field
- FR-measurements in pc-scales often show significant gradient *along* the jet in RM $\rightarrow$ Faraday screen is indeed close to the jet
- A large scale helical magnetic field in the jet can manifest itself as a RM gradient *across* the jet (Blandford 1993)
- Many groups are currently searching for such gradients trying to establish how common are ordered helical fields in parsec scale jets
- One very convincing case (3C273). A dozen or so claims in other sources.

Helical fields in parsec scales? Case of 3C273



Hovatta et al. in prep

Helical fields in parsec scales? Case of 3C273

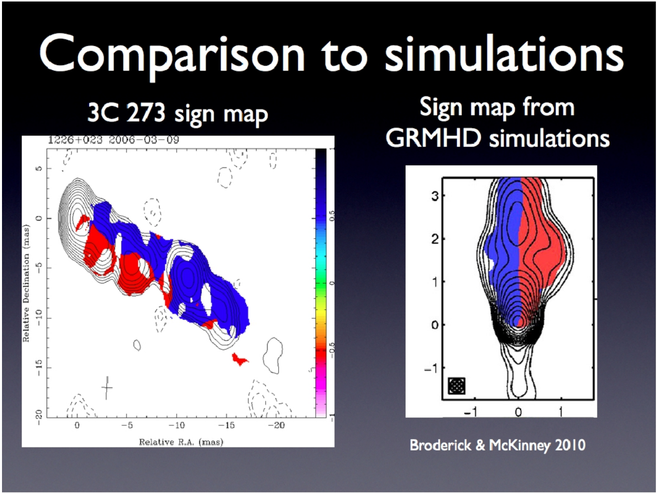


Image courtesy of T.Hovatta

Birefringence effects – Faraday conversion

- Faraday conversion can convert linear polarization to circular polarization
- Works in relativistic plasma where normal modes are elliptical unlike in thermal plasma
- Converts Stokes U to Stokes V
- Does not depend on charge sign or on B-field sign
- Since synchrotron radiation in uniform field only produces Stokes Q, one needs to first generate Stokes U (e.g., through internal Faraday rotation) and then convert this to Stokes V. Can explain the observed circ. pol. levels in excess of 1% in some sources.