Evidence for Highly Relativistic Jet Speeds on Kiloparsec Scales in the Superluminal Quasar 3C 345

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Question I

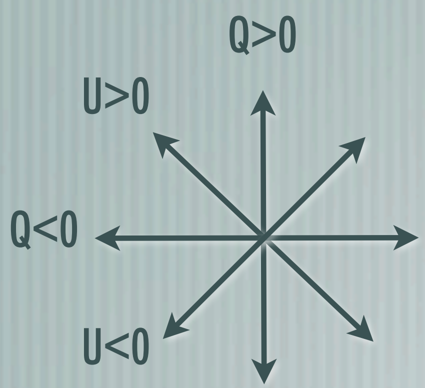
We know that many AGN jets are highly relativistic on parsec scales. *Does this continue to kiloparsec scales?*

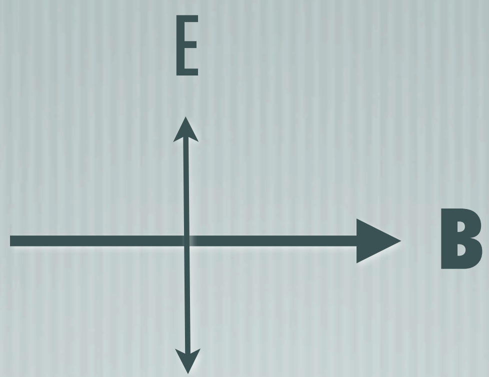
Question II

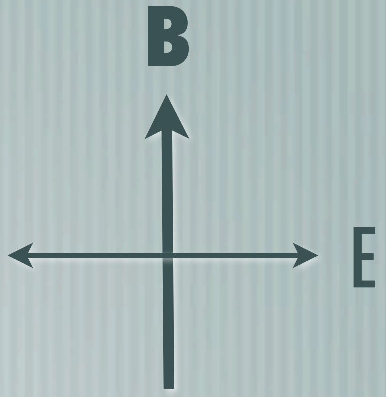
Models for the launching of jets suggest that the magnetic fields should be helical. There are signs of this on parsec scales. *Does this continue to kiloparsec scales?*

Magnetic Fields in AGN Jets on Kiloparsec Scales

In synchrotron radiation the **E** vectors are perpendicular to the source's **B** field.







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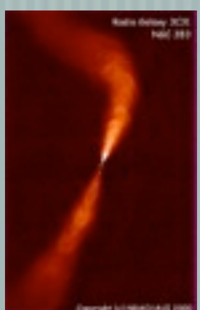

FR-I jets have **E** vectors parallel to the jet axis, so the inferred **B** is perpendicular to the jet axis.

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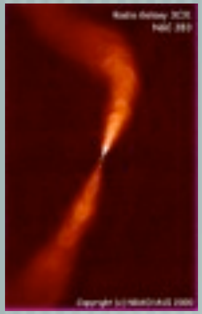

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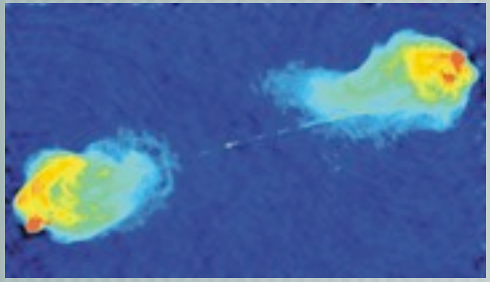


FR-II jets have **E** vectors perpendicular to the jet axis so the inferred **B** is parallel to the jet axis.

3C 345

Quasar with $z = 0.593$ (6.5 kpc/arcsec)

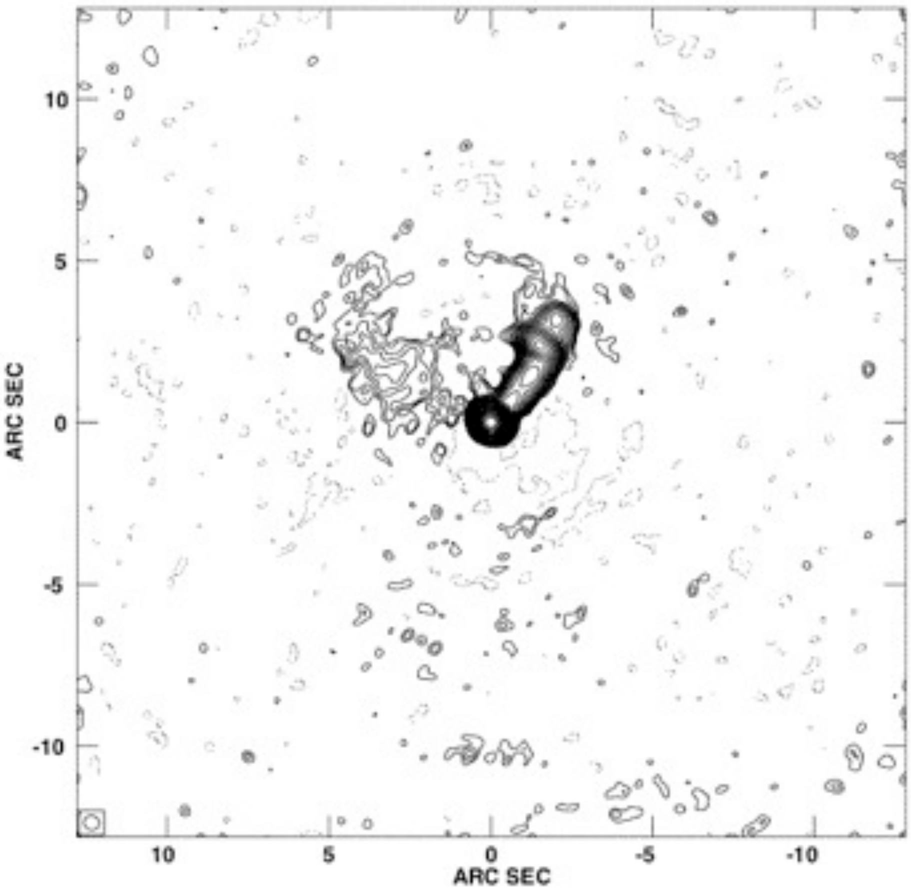
VLA calibrator at centimeter wavelengths

Well-studied superluminal with v_{app} up to 20c

FR-II seen nearly end-on (Kollgaard, Wardle, & Roberts 1989), so it should have a longitudinal **B** field

Over 1000 references in NED

3C 345 - 4.86 GHz



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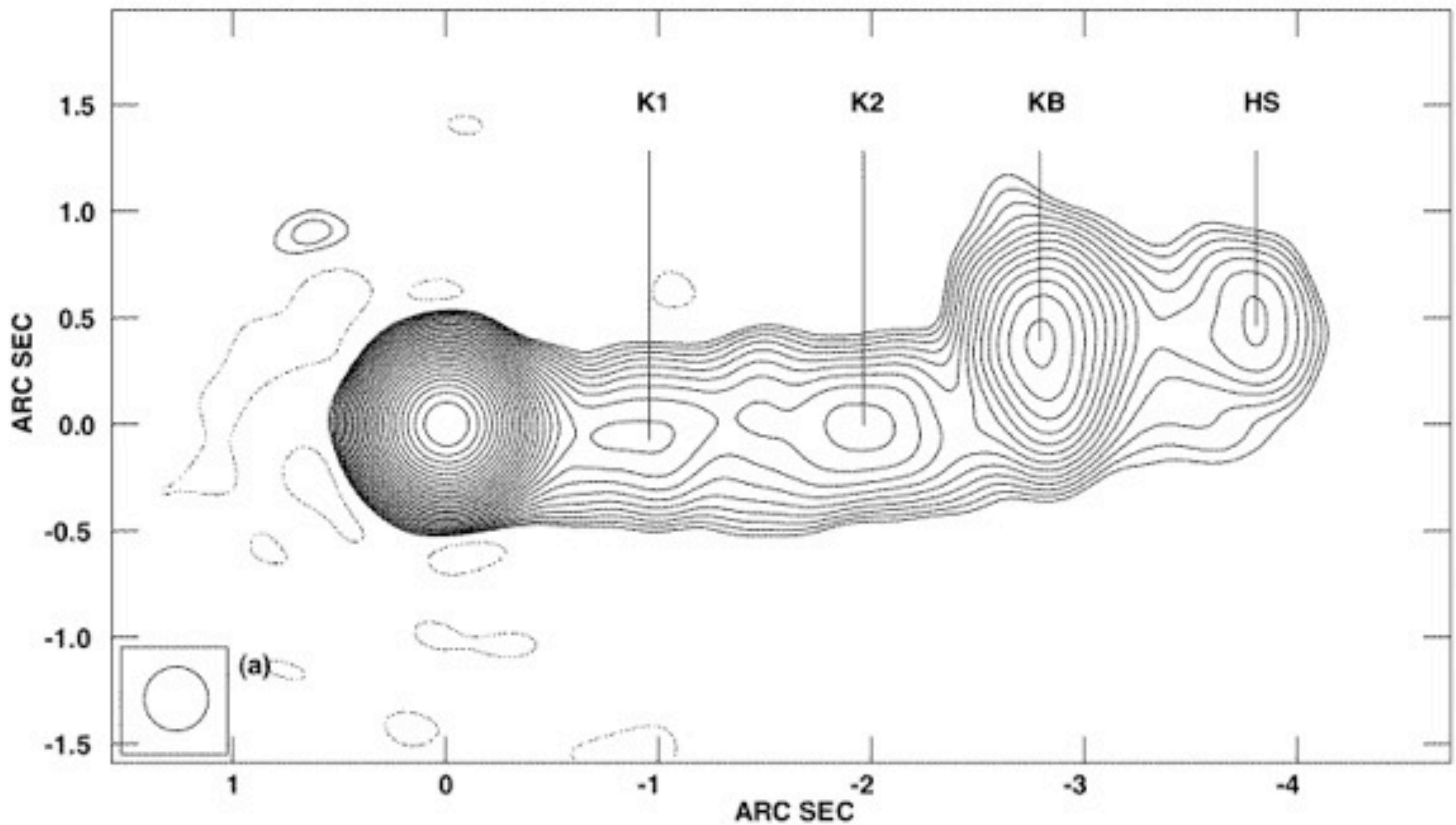
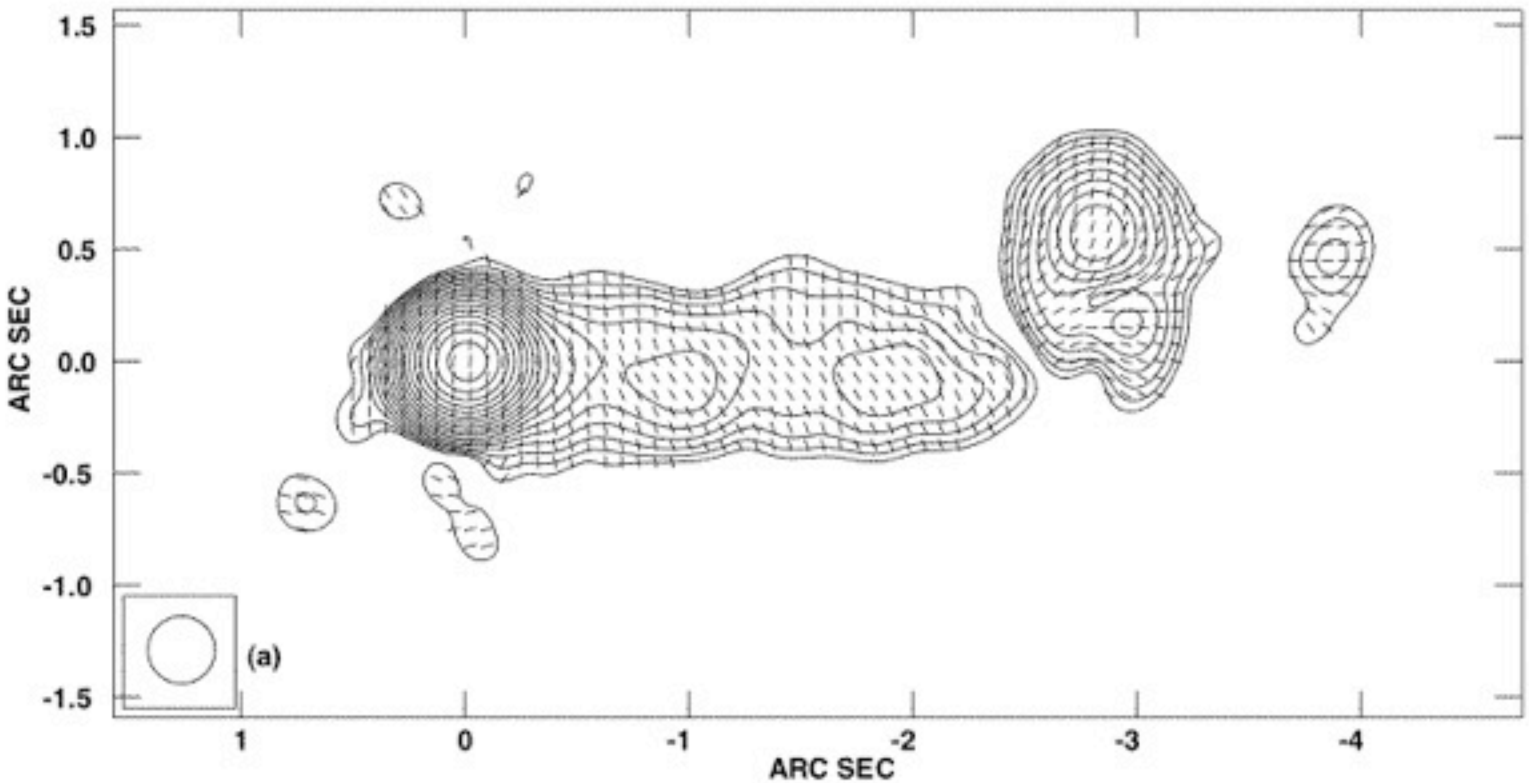


3C 345 - 4.86 GHz – Polarized Intensity with **E** Vectors



3C 345 Magnetic Field

The “twist” is about 35° in the center of the jet, none at the edges.

Naïve interpretation is that the **B** field is helical.

Alternate interpretation: Faraday rotation alters the observed **E** vector orientations.

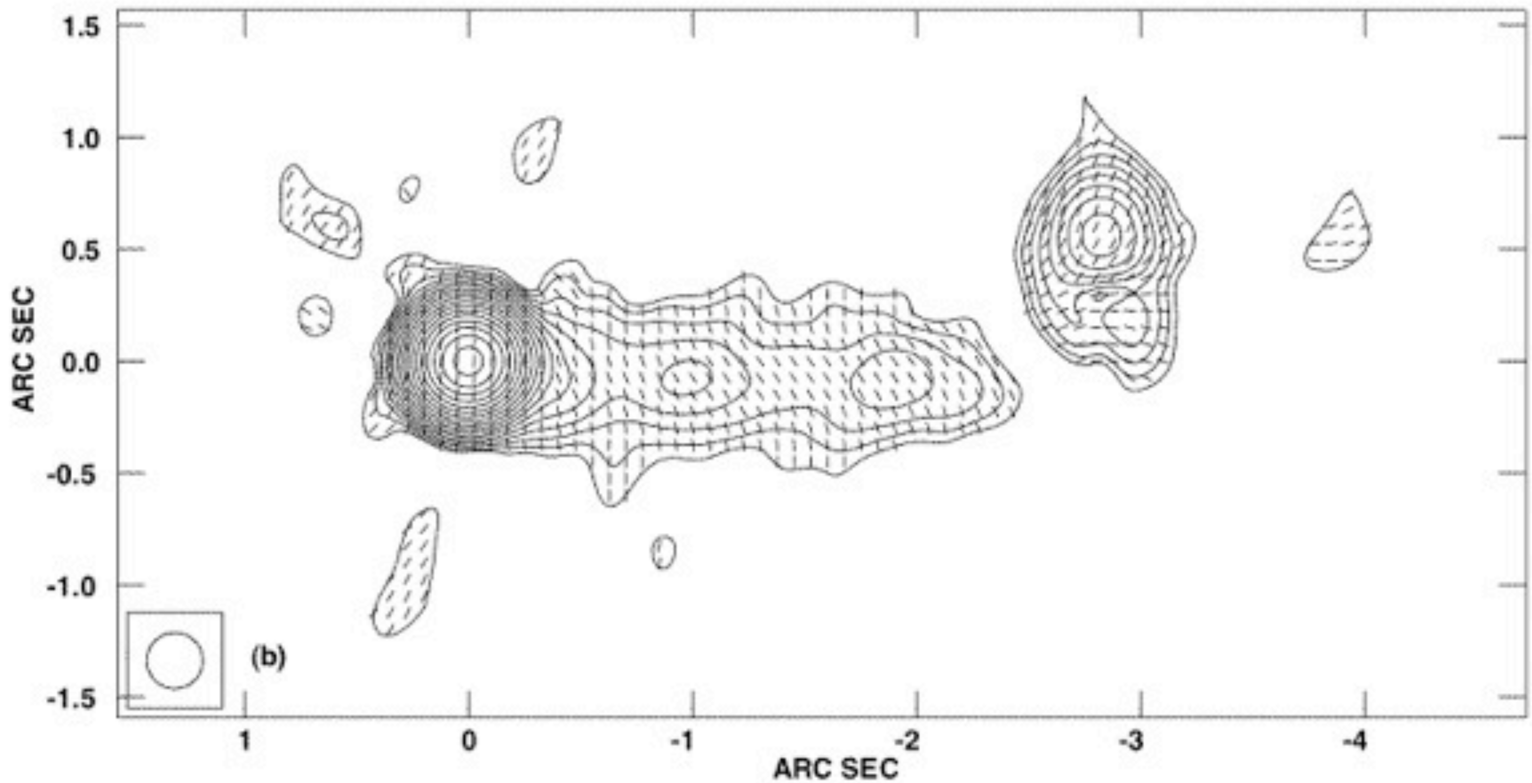
Is the "Twist" Due to Faraday Rotation?

Expect the electric vector position angle χ to vary with wavelength according to

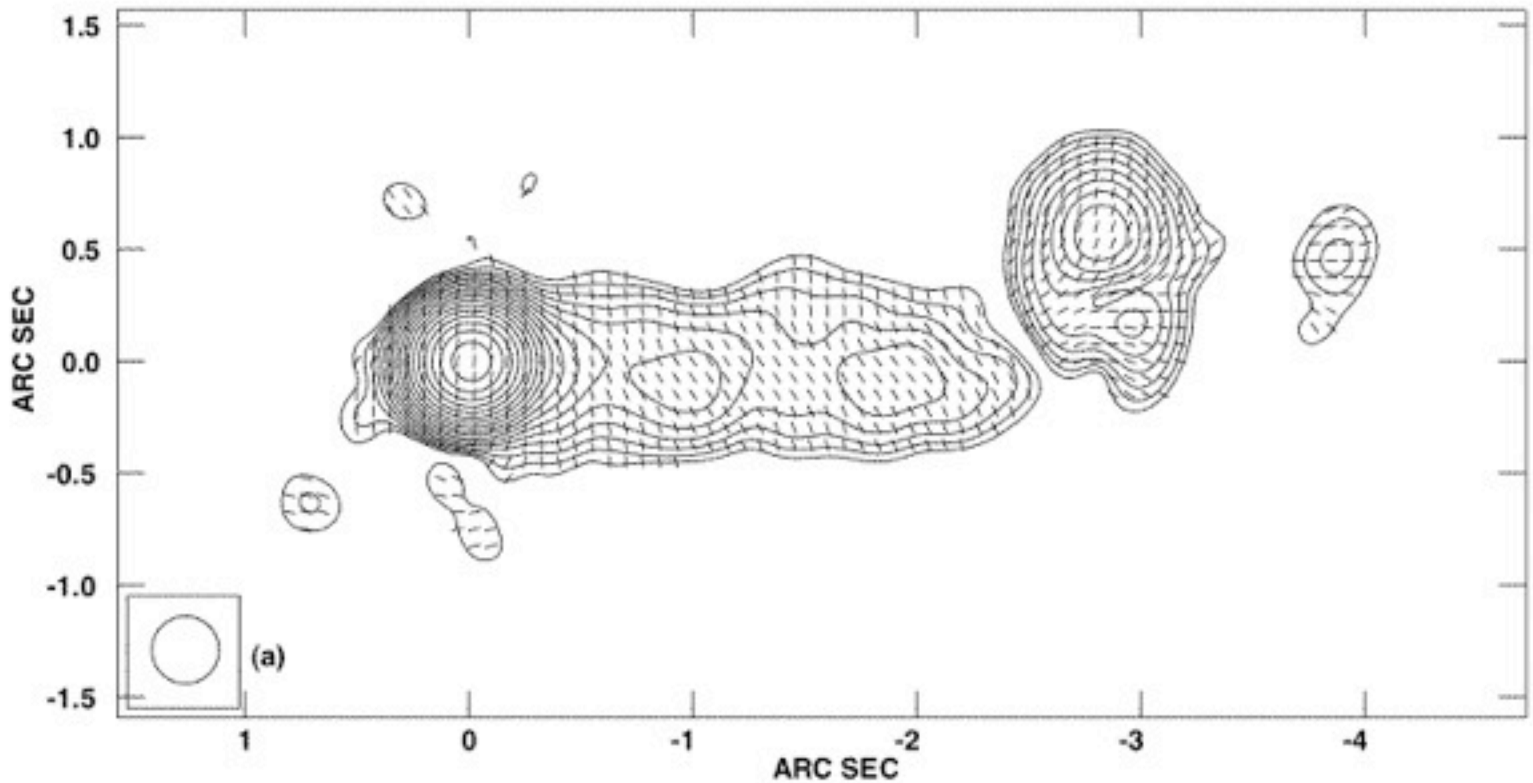
$$\chi(\lambda) = \chi_0 + RM\,\lambda^2$$

Observe at a second wavelength to measure both RM and χ_0.

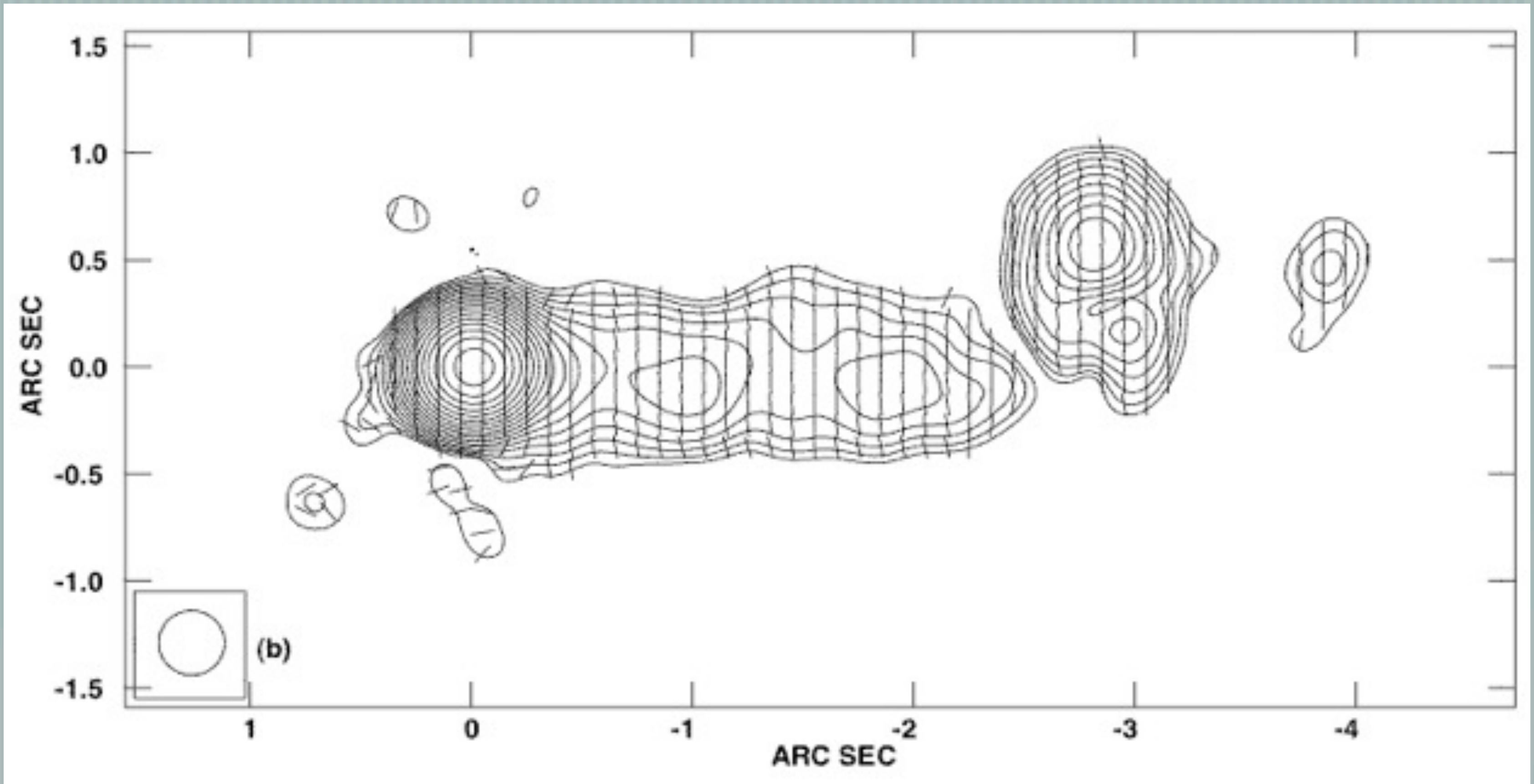
3C 345 - 8.44 GHz – Polarized Intensity with **E** Vectors



3C 345 - 4.86 GHz – Polarized Intensity with **E** Vectors



3C 345: $X_{5GHz} - X_{8GHz}$



3C 345

Faraday rotation is not the cause of the twisted electric vector structure.

Is the magnetic field actually helical, as it looks?

It's actually more complicated because the emerging radiation is the complex sum of that from different layers.

3C 345

A helical magnetic field in a transparent cylindrical jet does not look helical because of cancellation of Stokes *U* between front and back of the jet – the **B** field looks either longitudinal (Q>0) or transverse (Q<0) depending on the helix's pitch.

3C 345

Optical thickness could produce a twist by “hiding” the back of the jet so that U would not cancel out.

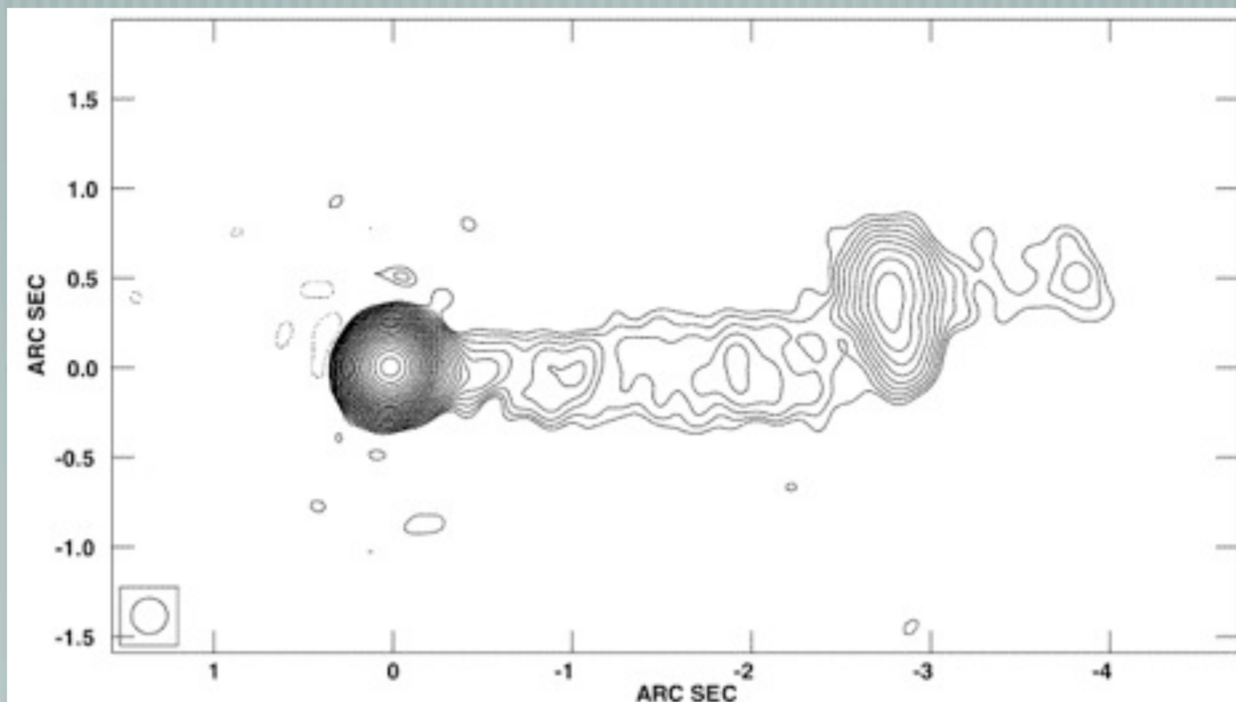
However, it would produce frequency structure that is not seen.

Thus we reject this possibility.

We need another explanation of the **E** vector twist.

3C 345 - 8.44 GHz

The jet is gently diverging:



3C 345

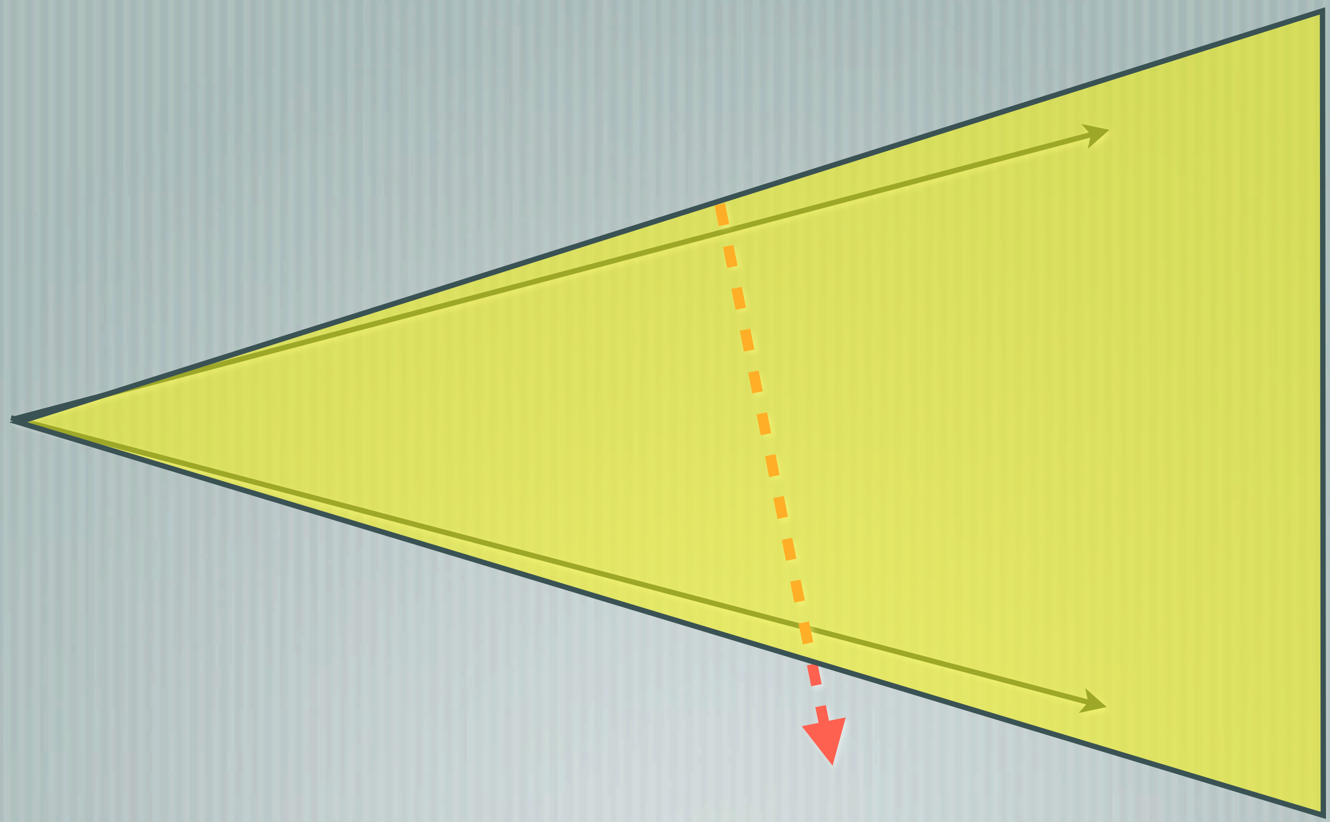
Half-opening angle is about $\phi_{\mathrm{apparent}} = 9^{\circ}$.

This suggests a diverging velocity field.

Differential Doppler boosting between front and back of the jet could break the symmetry that cancels U, producing a twist in the $\mathbf{E}$ vector orientations.

Can we use this to measure the jet velocity?

Differential Doppler Boosts



A Model for the 3C 345 Jet

Transparent uniform cylinder of relativistic electrons.

Helical magnetic field with surface field

$$B(\text{longitudinal})/B(\text{toroidal}) = b.$$

Diverging velocity field at $v = \beta c$ with angle to the jet axis

$$\phi(r) = \phi_i \, r^{\varepsilon},$$

where ϕ_i = intrinsic half-opening angle of jet, $0 \le r \le 1$ is the normalized radius, and ε is a parameter that we take to be unity.

Doppler boosts calculated from $\mathbf{v}(\mathbf{r})$.

A Model for the 3C 345 Jet

Symmetry of Q & U across jet requires that $\theta' \approx \pi/2$, which couples (i,β) through $\sin i \approx 1/\gamma$. Smaller parameter space to search (β, b)!

Intrinsic and apparent opening angles related by geometry as

$$\tan\phi_i = \tan\phi_a \sin i \approx \tan\phi_a / \gamma .$$

Increasing the velocity effectively narrows the jet opening angle.

Calculate profiles across the jet by integrating along many different lines of sight.

A Model for the 3C 345 Jet

$$I \propto \int B_{\perp}^{1+\alpha} D^{2+\alpha} dz$$

$$Q \propto m_{\max} \int B_{\perp}^{1+\alpha} D^{2+\alpha} \cos\left(2\chi_E\right) dz$$

$$U \propto m_{\max} \int B_{\perp}^{1+\alpha} D^{2+\alpha} \sin\left(2\chi_E\right) dz$$

$$\hat{\mathbf{e}} = \frac{\hat{\mathbf{n}} \times \hat{\mathbf{q}}}{\left|\hat{\mathbf{n}} \times \hat{\mathbf{q}}\right|}, \quad \hat{\mathbf{q}} = \hat{\mathbf{B}} + \hat{\mathbf{n}} \times (\hat{\mathbf{B}} \times \hat{\mathbf{v}})$$

A Model for the 3C 345 Jet

- For $\alpha = 1$ and $\theta' = \pi/2$, analytic models are possible in the fluid frame.
- Normalized profiles are ($-1 < x < 1$):

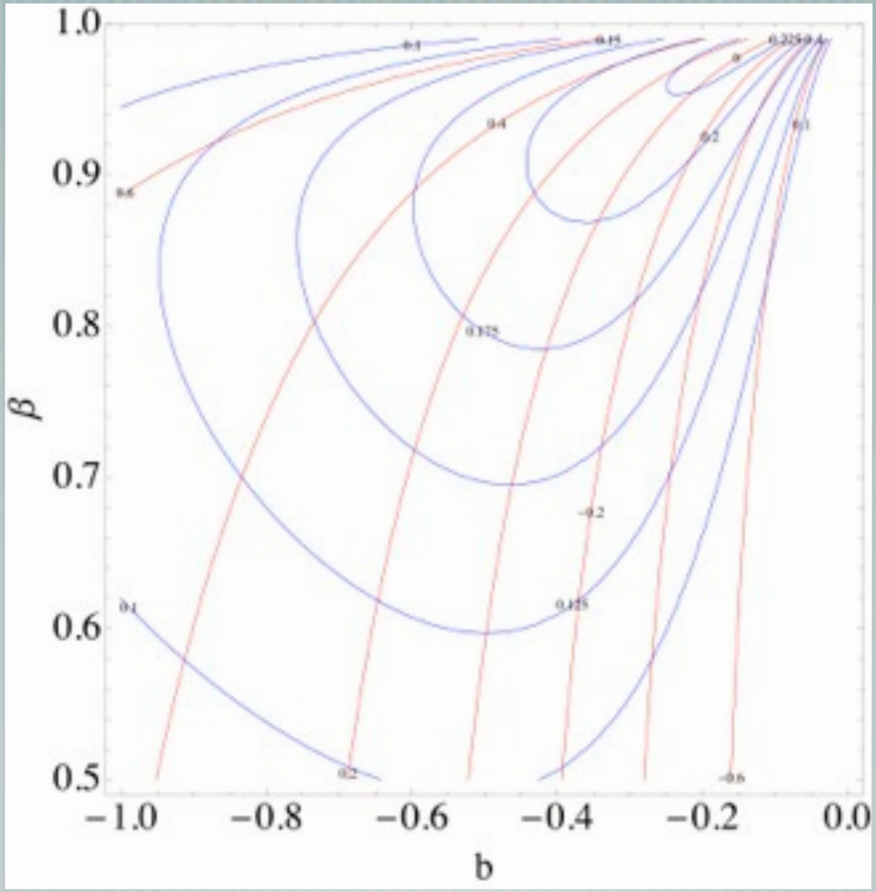
$$\frac{I(x)}{I(0)} = \frac{3b'^2 + 1 - x^2}{3b'^2 + 1}\left(1 - x^2\right)^{1/2},$$

$$\frac{Q(x)}{I(0)} = \frac{3}{4}\,\frac{3b'^2 - 1 + x^2}{3b'^2 + 1}\left(1 - x^2\right)^{1/2},$$

$$\frac{U(x)}{I(0)} = -\frac{9b'\beta\phi_a}{2(3b'^2 + 1)}\left(1 - x^2\right)^{3/2}.$$

A Model for the 3C 345 Jet

Q(0)/I(0) red, U(0)/I(0) blue:



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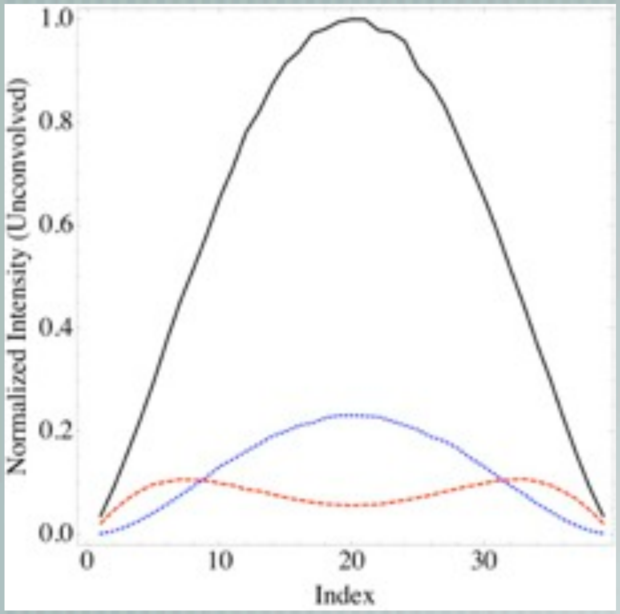
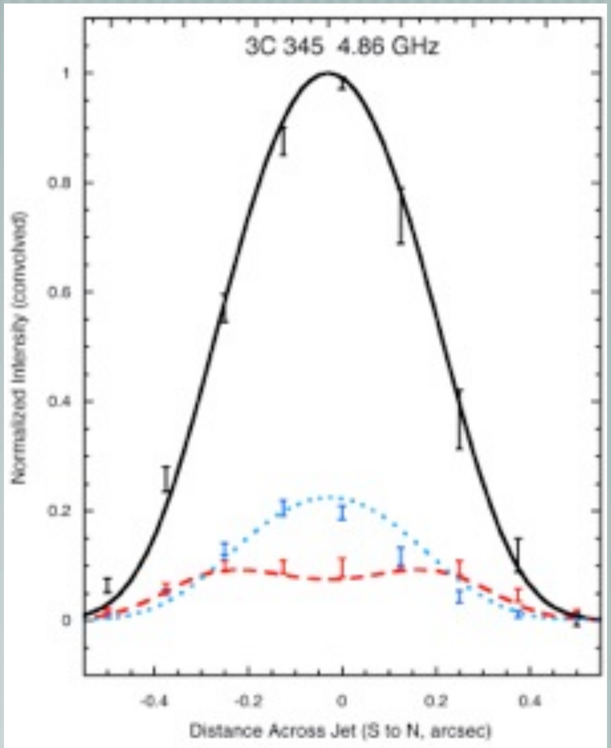


Convolve
with ===>
beam.



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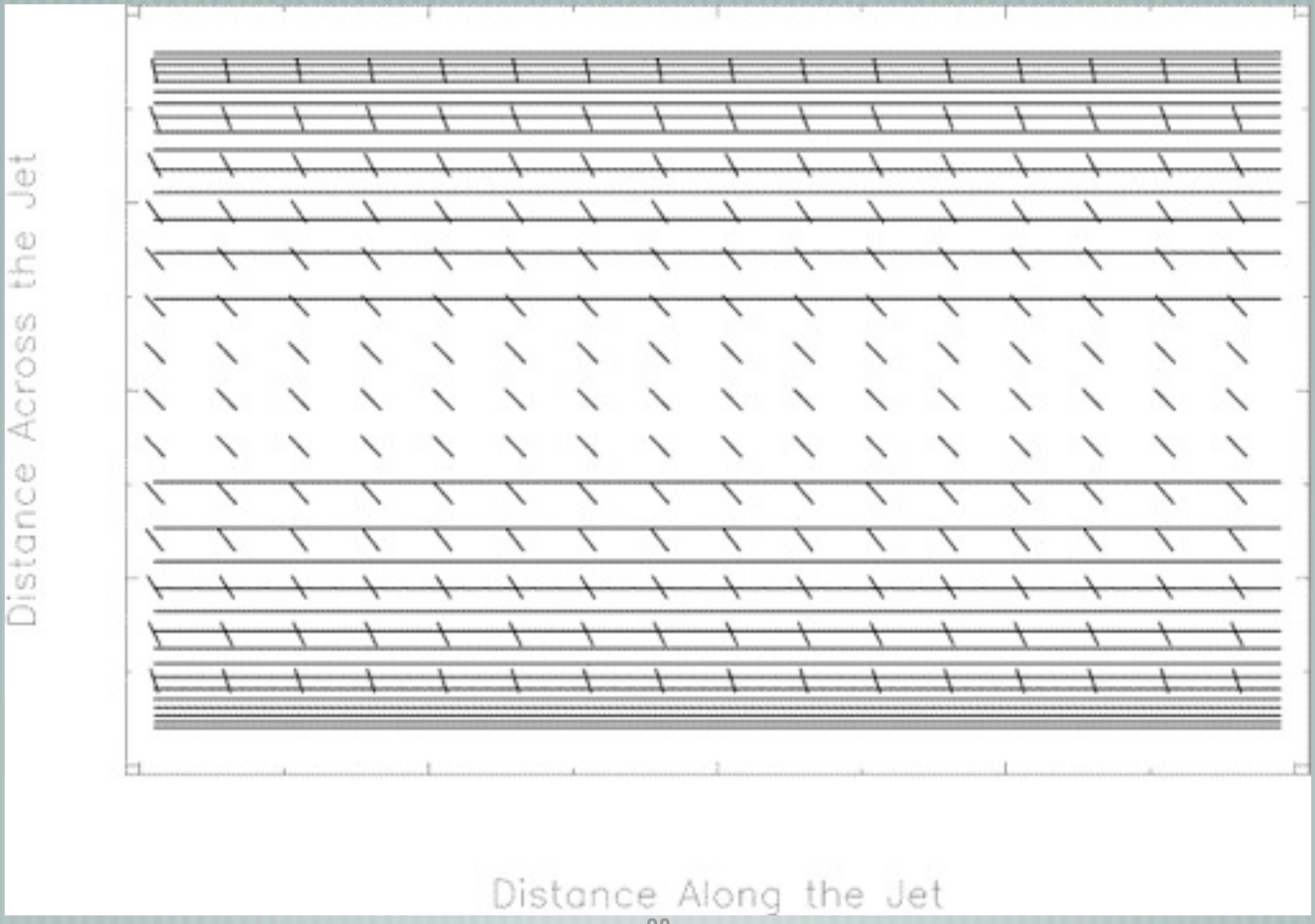

A Model for the 3C 345 Jet

Nominal parameters:

$$\beta \approx 0.97,\ \gamma \approx 4.1$$

$$\phi_i \approx 2.3^\circ$$

$$i \approx 14^\circ$$

$$b \approx -0.19$$

Conclusions

The 3C 345 jet has highly relativistic fluid speeds on kiloparsec scales, $0.95 \leq \beta \leq 0.99$.

This agrees with inverse-Compton models for the X-ray emission from the 3C 345 jet (Kharb et al. 2012).

The magnetic field in the 3C 345 jet is helical on kiloparsec scales.

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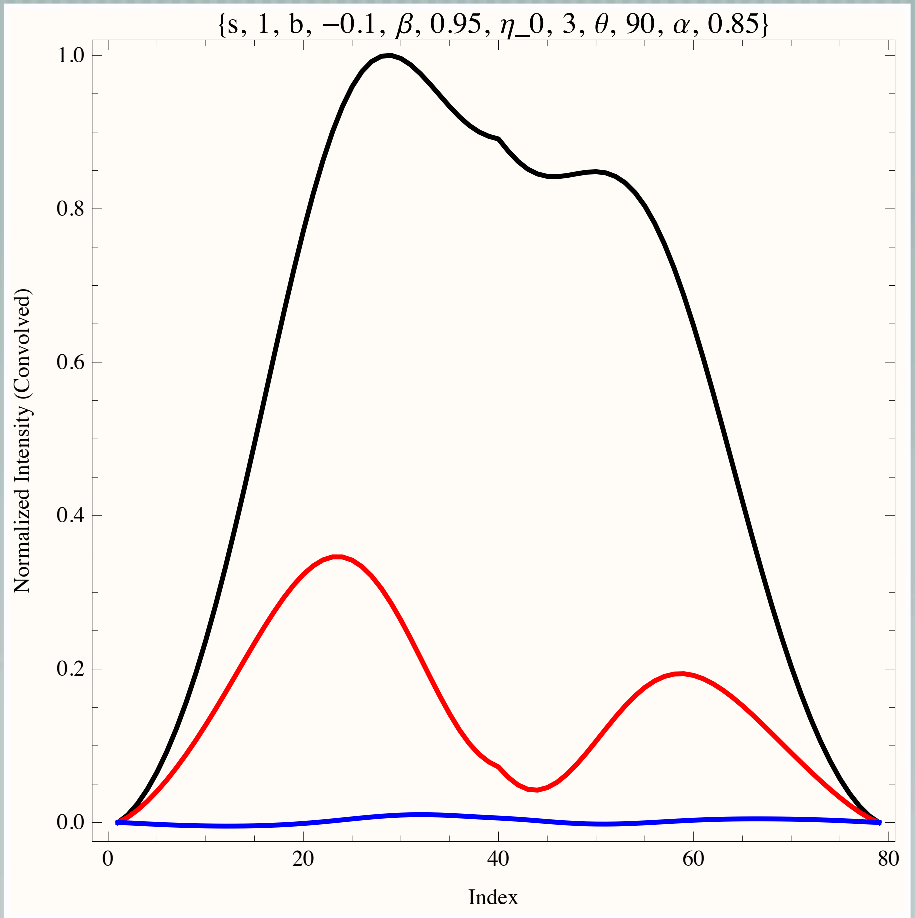
What About Other FR-II Jets?

- Best-observed ones are lobe dominated and thus are at larger inclinations to the line of sight than is 3C 345.
- Model predicts that 3C 345 if observed in the plane of the sky would exhibit transverse **E** vectors in the jets.
- Search is underway for other core-dominated AGN with “twisted” **E** vectors in their jets.

What About Other FR-II Jets?



Application to Parsec-Scales

- Jets are known to be relativistic and diverging on parsec scales.
- Thus the model should be applicable there.
- Possible explanation for those pc-scale jets that have **E** vectors that are neither aligned nor orthogonal.
- Another way to measure jet speeds on parsec scales.
- This measures fluid not pattern speed.