

Jet Collimation: 3C 279 Caught in the Act

D. C. HOMAN

*National Radio Astronomy Observatory, 520 Edgemont Road,
Charlottesville, VA 22903-2475, USA*

Abstract. We analyze a change in trajectory in a jet component of the quasar 3C 279. The component changes in speed and direction, and we find it to be moving with a Lorentz factor $\gamma \gtrsim 15$ at an initial angle of $\lesssim 1.2^\circ$ to the line of sight. The new trajectory of the component parallels that of the original superluminal feature from the early 1970s. We argue that the trajectory change is a collimation event occurring at $\gtrsim 1$ kiloparsec (deprojected). Comparison to independent constraints on the Doppler factor suggest this component is near equipartition values for magnetic field and particle energy.

1. Introduction

Faster-than-light or “superluminal” motion was originally predicted by Rees (1966) and first observed by Whitney et al. (1971) and Cohen et al. (1971) in the powerful radio quasar 3C 279 ($z = 0.536$). The illusion of superluminal speed results from highly relativistic motion toward the observer, with the moving material chasing the radiation it emits, creating a compression in the time sequence of events as seen by the observer. In radio loud quasars, like 3C 279, a pair of highly collimated, relativistic plasma jets stream outward from the nucleus, and if one of these jets points within a small angle, θ , of our line of sight, then pattern motion at some intrinsic speed, $\beta = v/c < 1$, will appear to move across the sky with an apparent speed given by:

$$\beta_{\text{app}} = \frac{\beta \sin \theta}{1 - \beta \cos \theta}, \quad (1)$$

which can greatly exceed unity.

The radio jet in 3C 279 is a particularly interesting example with components ejected at multiple position angles and apparent speeds. The motion of the original superluminal feature, as summarized by Cotton et al. (1979) who analyzed the six available epochs spanning the period 1970–1972, was along a position angle of $-142^\circ \pm 2^\circ$ at $0.5 \pm 0.1 \text{ mas yr}^{-1}$. For a modern cosmology of $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$, this corresponds to $\beta_{\text{app}} = 17 \pm 3$. During the 1980s, Unwin et al. (1989) tracked another major component from 3C 279 which they called “C3”. Component C3 was found to move along a position angle of -134° with a much smaller speed of only $0.12 \pm 0.02 \text{ mas yr}^{-1}$ corresponding to $\beta_{\text{app}} = 4 \pm 1$.

At the very end of 1984, Unwin et al. (1989) mark the emergence of a new component they call C4. Component C4 is an extremely strong and compact

feature which has been tracked up to the present day by a number of programs; however, the most detailed and complete results to date were presented by Wehrle et al. (2001). They followed C4 from 1991 to the end of 1997 with 22 GHz observations and from 1995 to 1997 at 43 GHz. They find the component to be steadily moving along a position angle of -114° with a speed of $0.26 \pm 0.01 \text{ mas yr}^{-1}$ which corresponds to 8.9 ± 0.3 times the speed of light in our choice of cosmology. They extrapolate an origin epoch for the component of 1984.7 ± 0.3 , consistent with the first observation of C4 by Unwin et al. (1989). Wehrle et al. (2001) do analyze a dip in speed of C4 around 1994 which coincides with small changes (a few degrees) of the trajectory on the sky; however, the component resumes its previous motion and trajectory by the end of 1995.

Here we present results from the VLBA 2 cm survey (see Zensus et al., these proceedings, page 27) showing that after 1998, component C4 distinctly changes its trajectory on the sky and its apparent speed. This change in speed and direction puts C4 on an essentially parallel track to the original superluminal component with essentially the same speed as observed for that original component.

2. Observations and Results

Our observations of 3C 279 from the VLBA 2 cm survey consist of 11 epochs spanning the interval from 1995.5 to 2002.3. We have also incorporated 2 cm VLBA results from the Brandeis University parsec-scale jet monitoring project (Homan et al. 2001, 2002; Ojha et al. to be submitted) which adds six closely spaced epochs during 1996 and a seventh epoch at the end of 1997. We measured component positions both in the image plane, by fitting point sources at the peak locations of the core and C4, and in the (u, v) -plane by fitting 2-3 point components to the core region and a single elliptical Gaussian to C4. Image plane positions are used in Figures 1 and 2, and positions from both approaches are used in computing proper motion.

Figure 1 shows an image of 3C 279 from our March 1997 epoch. Superimposed on this image is the position of component C4 from each of the 18 epochs we compiled. Approximate positions for the original superluminal component are also included on the figure for comparison. Figure 2 is a more detailed plot of the component position versus epoch and also depicts the deconvolved FWHM Gaussian sizes of C4 in each epoch.

Vector proper motions were computed from the (x, y) component positions. The motions were computed over two different intervals, one prior to the change in trajectory and one after. We were unable to decide whether epoch 1998.2 should be classified with the motion prior to the change or after the change, and we found that it made little difference which choice we made. Table 1 summarizes the vector motions from a variety of approaches. From these results we take the motion prior to the ‘‘bend’’ to be along a position angle of $-114^\circ \pm 1^\circ$ at $0.25 \pm 0.02 \text{ mas yr}^{-1}$ corresponding to 8.5 ± 0.7 times the speed of light. After the bend we take the motion to be along a position angle of $-139^\circ \pm 1^\circ$ at $0.40 \pm 0.02 \text{ mas yr}^{-1}$ which corresponds to 13.7 ± 0.7 times the speed of light.

Figure 3 depicts the change in component flux density, size along the -114° position angle, and brightness temperature as a function of epoch. Prior to the

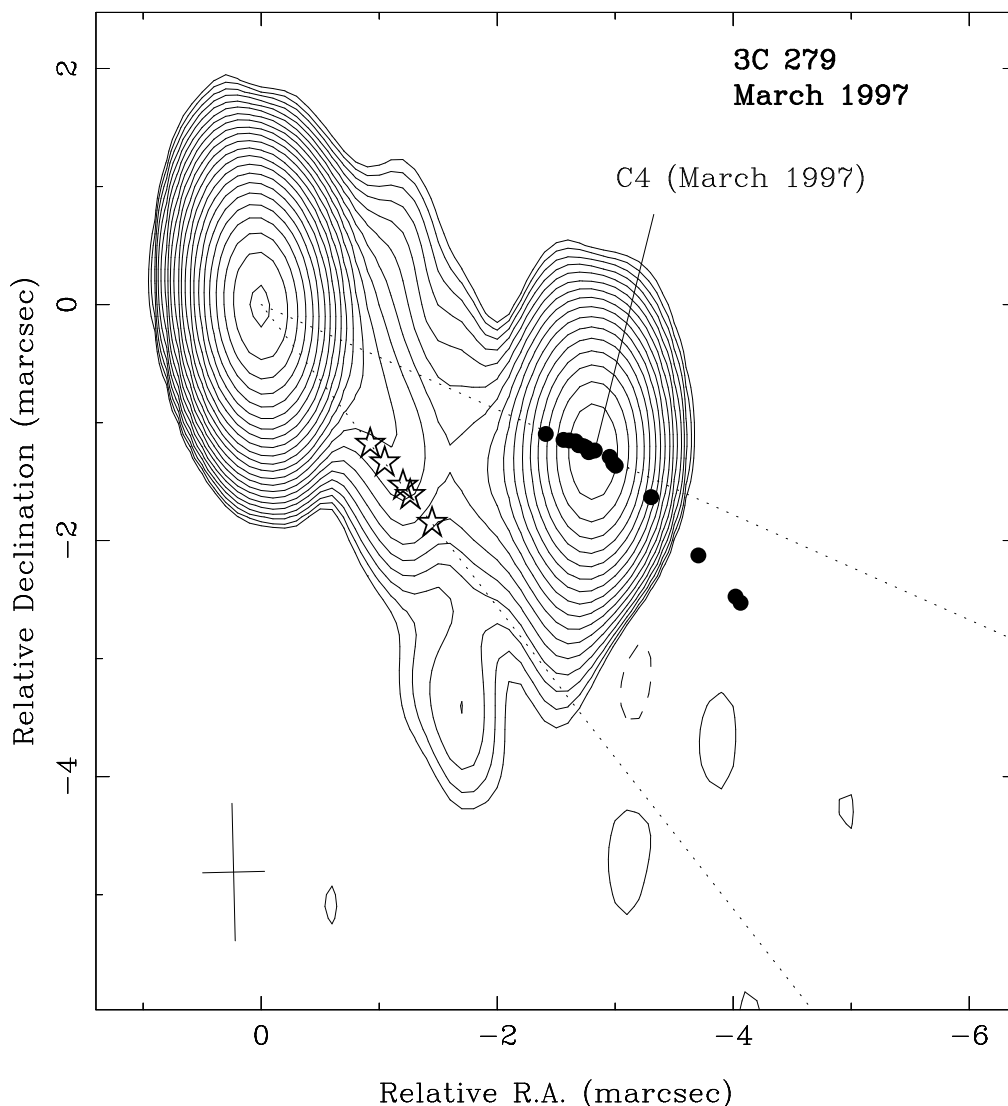


Figure 1. A $\lambda 2$ cm, VLBA image of 3C 279 in March 1997. Overlaid on this image are component positions for C4 (solid dots) measured from 2 cm VLBA maps taken from the period 1995.5 to 2002.3. Open stars indicate the approximate locations measured for the original superluminal component (distances and position angle taken from Cotton et al. 1979). Dashed lines mark the -142° and -114° position angles respectively. See the 2 cm Survey web page: <http://www.cv.nrao.edu/2cmsurvey/> for a movie of 3C 279.

sharp change in motion sometime in 1998, the component increases in flux density by 50% and decreases in size along the direction of motion by a factor of two. These events seem to come before the change in motion, suggesting the component is already interacting with its environment while it is still propagating along the original direction of motion.

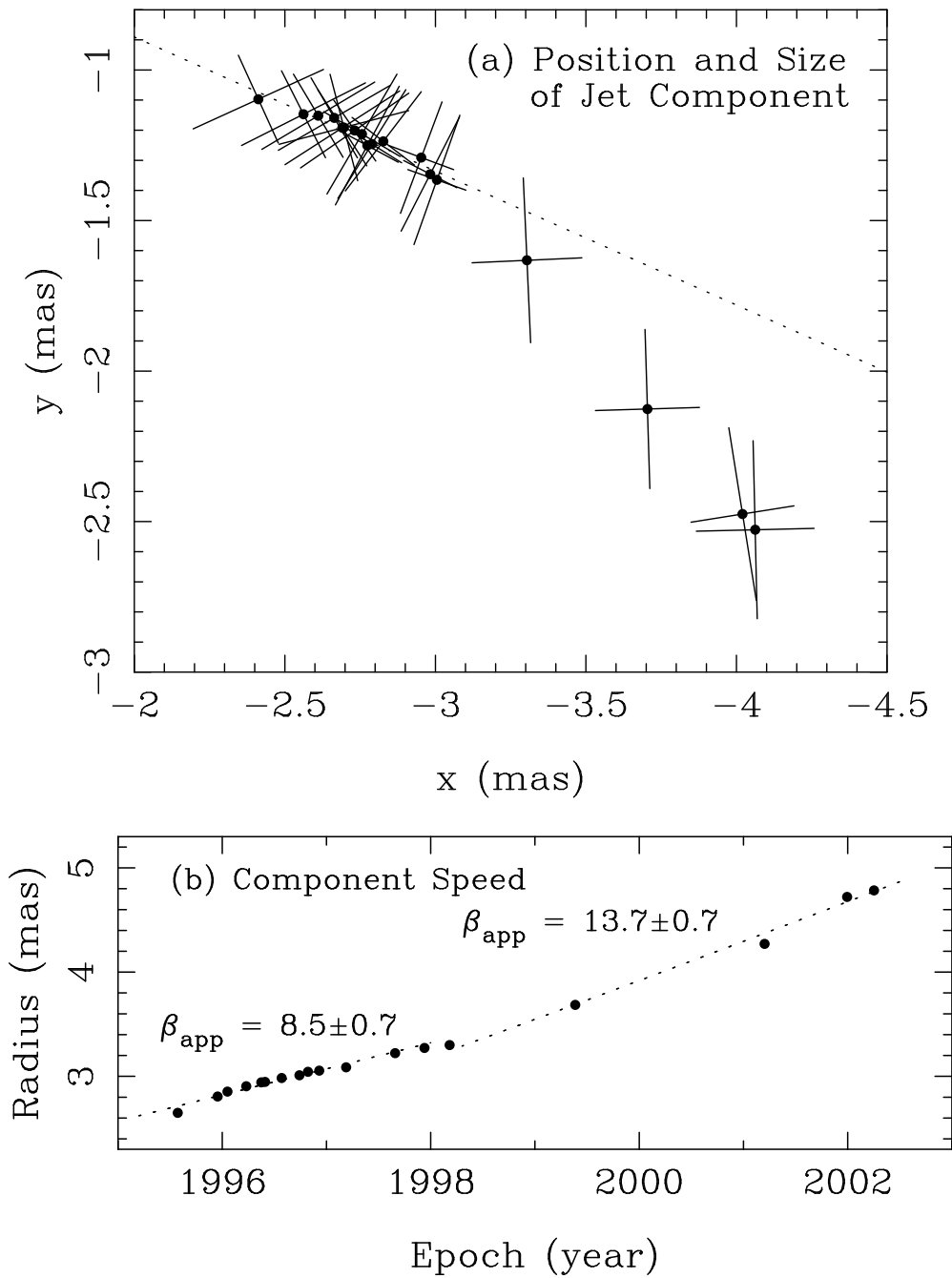


Figure 2. Panel (a): Plot of the (x, y) component position and deconvolved FWHM sizes of the fitted elliptical Gaussian. Panel (b): Plot of radial component position versus time with lines representing the projection of the fitted vector motion. Speeds derived from the vector motion fits are indicated.

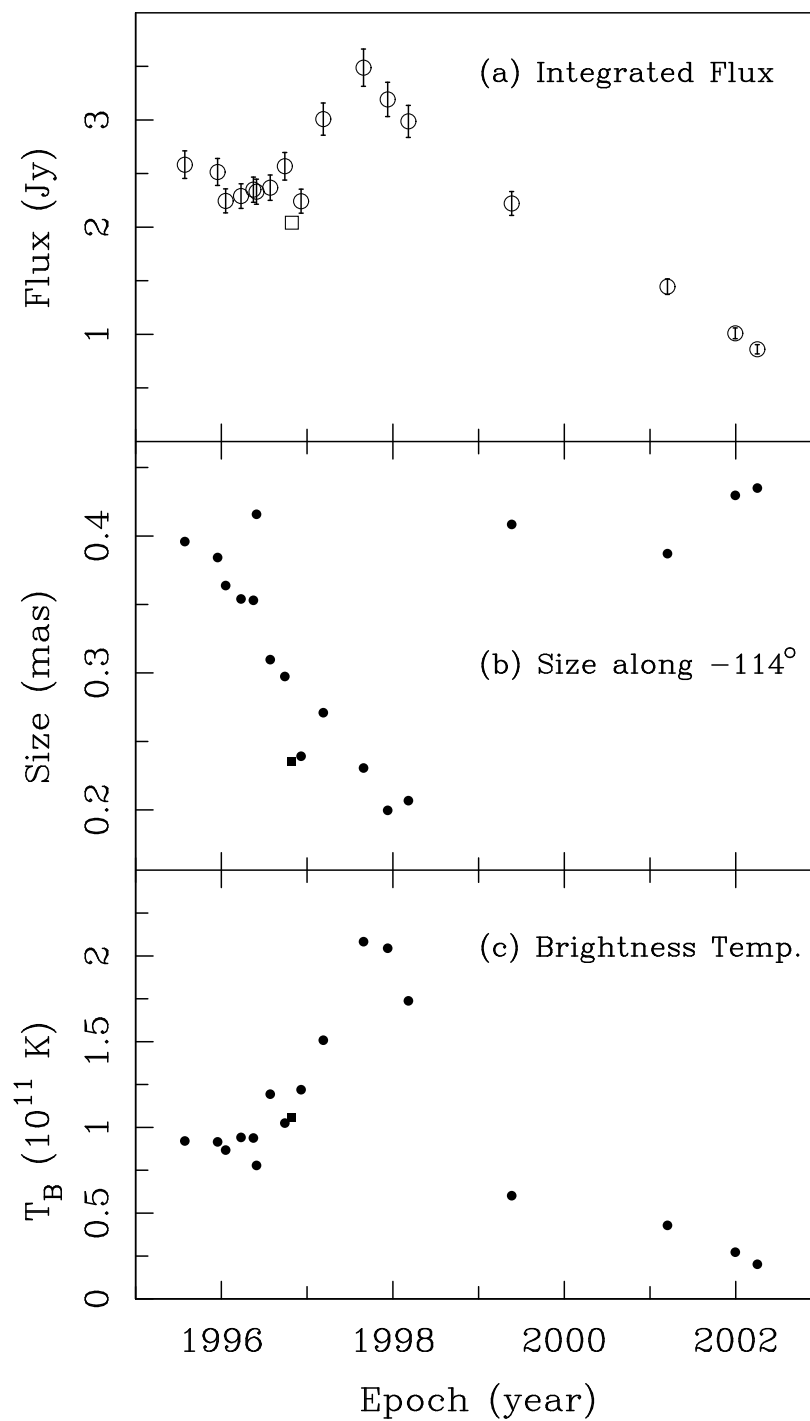


Figure 3. Plots of component flux density (panel (a)), FWHM size along the -114° position angle (panel (b)), and brightness temperature (panel (c)) versus epoch. The square symbols represent a poorly calibrated epoch with flux density $\sim 10\%$ low.

Table 1. Vector motion of C4 computed for various ranges of epochs (N = number) for positions fit either the image or (u, v) -plane.

Epoch Range	N	Positions	μ (mas yr ⁻¹)	PA (deg)
1995.57–1997.94	13	Image	0.24 ± 0.01	-113.3 ± 1.8
1995.57–1998.18	14	Image	0.23 ± 0.01	-114.9 ± 1.6
1995.57–1997.94	13	(u, v)	0.27 ± 0.01	-113.5 ± 1.4
1995.57–1998.18	14	(u, v)	0.26 ± 0.01	-115.6 ± 1.4
1998.18–2002.25	5	Image	0.39 ± 0.02	-138.2 ± 2.3
1999.39–2002.25	4	Image	0.42 ± 0.02	-139.7 ± 3.4
1998.18–2002.25	5	(u, v)	0.39 ± 0.01	-138.1 ± 0.9
1999.39–2002.25	4	(u, v)	0.40 ± 0.01	-139.2 ± 0.8

3. Analysis

The apparent speed of this component has increased by more than 50% and the trajectory on the sky has changed by 25° . According to equation 1, the apparent speed can increase either due to a increase in the intrinsic speed, β , or by a change in angle to the line of sight. We consider an increase in β to be unlikely, as something must impart additional momentum to the component; however, a change in angle to the line of sight is quite consistent with the observed change in angle on the plane of the sky, so in this analysis we take β to be fixed and allow only the angle, θ , to change.

Figure 4 plots the Doppler factor, $\delta = 1/\gamma(1-\beta \cos \theta)$ where $\gamma = 1/\sqrt{1-\beta^2}$, versus the apparent motion, β_{app} . Lines of constant speed (Lorentz factor, γ) and lines of constant angle are shown on the figure. $\gamma = 10$ is clearly too small and cannot accommodate speeds greater than $10c$. The lines for $\gamma = 15$ or $\gamma = 20$ are more reasonable, and the change in speed from $8.5c$ to $14c$ can be accommodated by either an increase or decrease in the angle of the motion with the line of sight.

To decide between the two possibilities of increasing or decreasing θ , we must look at the corresponding change in Doppler factor which will scale the flux density of the jet component like $S \propto \delta^{3.5}$, appropriate for a discrete component with a spectral index of 0.5. For a decreasing θ (i.e., a trajectory bent towards the line of sight), the Doppler factor more than doubles between $8.5c$ and $14c$ along the $\gamma = 15$ curve. This would predict an increase in flux density of the component of more than an order of magnitude; however, from Figure 2b, it is clear that the flux density of the component changes by no more than a factor of two, and after 1998 the flux density only decreases. For increasing θ (i.e., a trajectory bent away from the line of sight) the situation is much better, and the Doppler factor decreases by approximately 20% along the $\gamma = 15$ curve. This corresponds to a decrease in component flux density of a factor of two.

From this analysis assuming fixed component speed, we estimate $\gamma \gtrsim 15$ with an initial angle to the line of sight of $\theta \lesssim 1.2^\circ$ increasing in the bend to become $\theta \lesssim 2.5^\circ$. The bend in the plane of the sky appears to be 25° ; however,

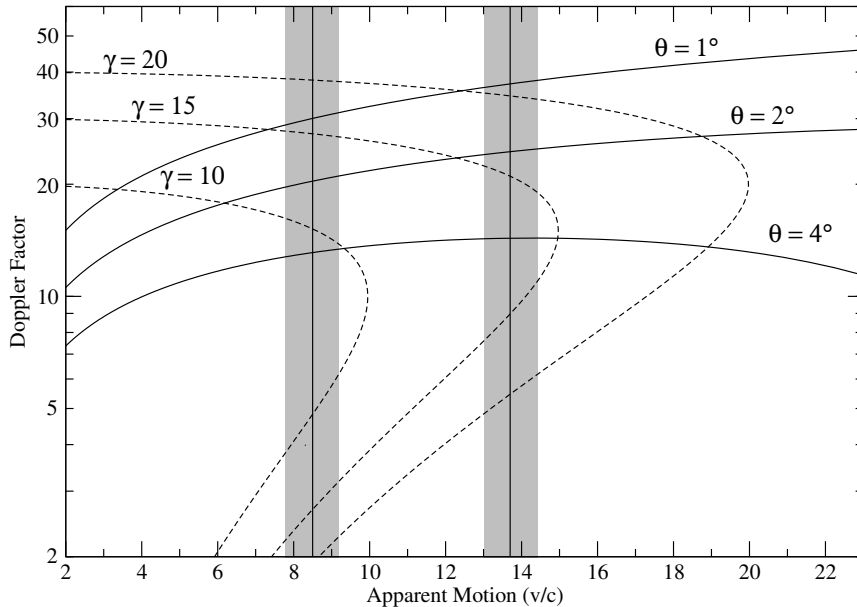


Figure 4. Plot of Doppler factor versus apparent speed. Dashed contours indicate lines of constant bulk Lorentz factor, and solid contours indicate lines of constant angle to the line of sight. Vertical lines with gray envelopes indicate the component speed before and after the bend.

deprojected, this bend is only $\sim 0.5^\circ - 1^\circ$, consistent in size with the bend along the line of sight. It is interesting to note that our value of $\gamma \gtrsim 15$ agrees well with that of Cohen et al. (these proceedings, page 177) who estimate $\gamma = 19$ for 3C 279 from an largely independent argument using variability Doppler factor.

4. Discussion

4.1. Doppler Factor and Equipartition

From the angles and Lorentz factors estimated above, we can derive approximate limits on the Doppler beaming factor of this jet feature before and after the bend. We find $\delta \gtrsim 27$ prior to the change in trajectory and $\delta \gtrsim 21$ after the change.

It is interesting to compare these values to the completely independent estimate of the Doppler factor made by Homan & Wardle (2000). They fit a spectral turnover for this individual VLBI component in epoch 1997.94, just before the change in trajectory described here. They found $\delta = 18.2_{-2.8}^{+5.6} \eta^{1/7}$ where η is the ratio of energy in the magnetic field to energy in the radiating particles: $\eta = U_B/U_p$.

The reasonable agreement between these two independent determinations of the Doppler factor of component C4, would seem to argue that the radiating particles and magnetic field must be near the equipartition value of $\eta \sim 1$, with departures from equipartition in favor of excess magnetic field energy.

4.2. What Caused the Bend?

We argue above that C4 interacts with its environment prior to the change in trajectory, resulting in decreased angular size along the -114° position angle and increased flux density. It seems clear, therefore that C4 has been deflected onto its new trajectory. A random collision would be unlikely to deflect C4 in just the right fashion to have essentially the same speed *and* direction on the sky as the original superluminal component detected in 1971. It is important to stress that the trajectory of C4 is *parallel* to that of the original component; C4 is not following the actual path of that component (see Fig. 1).

We conclude that the change in trajectory is a collimation event resulting from the interaction of C4 with the boundary between the jet outflow and the interstellar medium. The exact nature of this boundary and interaction, we don't know; however, it is interesting to note that this collimation event occurred at a deprojected distance from the nucleus of $\gtrsim 1$ kpc.

We also speculate that the large range of component speeds and angles observed in 3C 279 result only from small differences in the initial angle of ejection. Intrinsically, these components all may have very similar Lorentz factors, as do C4 and the original superluminal component.

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