

JET COLLIMATION IN ACTION: REALIGNMENT ON KILOPARSEC SCALES IN 3C 279

D. C. HOMAN,¹ M. L. LISTER,¹ K. I. KELLERMANN,¹ M. H. COHEN,² E. ROS,³ J. A. ZENSUS,³
 M. KADLER,³ AND R. C. VERMEULEN⁴

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ABSTRACT

We report a change in the trajectory of a well-studied jet component of the quasar 3C 279. The component changes in apparent projected speed and direction, and we find it to be moving with a Lorentz factor $\gamma \approx 15$ at an initial angle of $\lesssim 1^\circ$ to the line of sight. The new trajectory of the component has approximately the same speed and direction as an earlier superluminal feature, originally seen in the early 1970s. The new direction for the component is also much better aligned with larger scale Very Large Baseline Array and Very Large Array structure out to $0''.1$. We suggest that the trajectory change is a collimation event occurring at ≈ 1 kpc (deprojected) along the jet. While the change in trajectory on the sky appears to be 26° , the intrinsic change is $\lesssim 1^\circ$. We estimate the Doppler factor prior to the change in direction to be $\delta \approx 28$ and after the change to be $\delta \approx 23$. A comparison with independent constraints on the Doppler factor suggests that the energy in the radiating particles cannot greatly exceed the energy in the magnetic field unless the volume filling factor is very much less than 1.

Subject headings: galaxies: active — galaxies: jets — galaxies: kinematics and dynamics — quasars: individual (3C 279)

1. INTRODUCTION

Faster-than-light or “superluminal” motion was originally predicted by Rees (1966) and was first observed by Whitney et al. (1971) and Cohen et al. (1971) in the powerful radio quasar 3C 279 (1253–055; $z = 0.536$). The illusion of superluminal speed results from highly relativistic motion directed 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 quasars, like 3C 279, a pair of highly collimated, relativistic plasma jets stream outward from the nucleus or core, and if one of these jets points within a small angle, θ , of our line of sight, then pattern motion with 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 moving along 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 ± 0.1 mas yr⁻¹. For a modern cosmology of $H_0 = 70$ km s⁻¹ Mpc⁻¹, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$, this corresponds to $\beta_{\text{app}} = 16 \pm 3$. The Very Large Array (VLA) observations of de Pater & Perley (1983) show that knot C at $0''.1$ had a position angle of -145° in a nearly direct line with the superluminal motion detected on length scales 50 times smaller. The observational picture became less

clear during the 1980s when Unwin et al. (1989) tracked another superluminal component from 3C 279 that they call C3. Component C3 was found to move along a different position angle of -134° with a much smaller speed of only 0.12 ± 0.02 mas yr⁻¹ corresponding to $\beta_{\text{app}} = 4 \pm 1$.

At the very end of 1984, Unwin et al. (1989) note the emergence of a new component they call C4. Component C4 is an extremely strong and compact feature that has been tracked up to the present by a number of programs. 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 found the component to be moving along a position angle of -114° with a speed of 0.26 ± 0.01 mas yr⁻¹ that corresponds to 8.2 ± 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) discuss a dip in speed of C4 around 1994 that coincides with small changes (a few degrees) of the trajectory on the sky. Whether this small change in the motion is related to the large changes reported here is unclear; however, the component had resumed its previous motion and trajectory by the end of 1995.

Here we present results from the Very Long Baseline Array⁵ (VLBA) 2 cm Survey⁶ (Kellermann et al. 1998) showing that after 1998, the trajectory of C4 changes in both apparent speed and direction. The new trajectory for C4 is on an essentially parallel track to the 1970s superluminal component with essentially the same speed as originally observed for that component.

2. OBSERVATIONS AND RESULTS

Our observations of 3C 279 from the VLBA 2 cm Survey consist of 12 epochs spanning the interval from 1995.5 to 2002.9 (for an animation, see footnote 6). We have also incorporated 2 cm VLBA results from the Brandeis University

¹ National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903; dhoman@nrao.edu, mlister@nrao.edu, kkellerm@nrao.edu.

² Department of Astronomy, MS 105-24, California Institute of Technology, Pasadena, CA 91125; mh@astro.caltech.edu.

³ Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany; ros@mpifr-bonn.mpg.de, azensus@mpifr-bonn.mpg.de, mkadler@mpifr-bonn.mpg.de.

⁴ Netherlands Foundation for Research in Astronomy, Postbus 2, NL-7990 AA Dwingeloo, Netherlands; rvermeulen@astron.nl.

⁵ The VLBA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

⁶ See <http://www.cv.nrao.edu/2cmsurvey>.

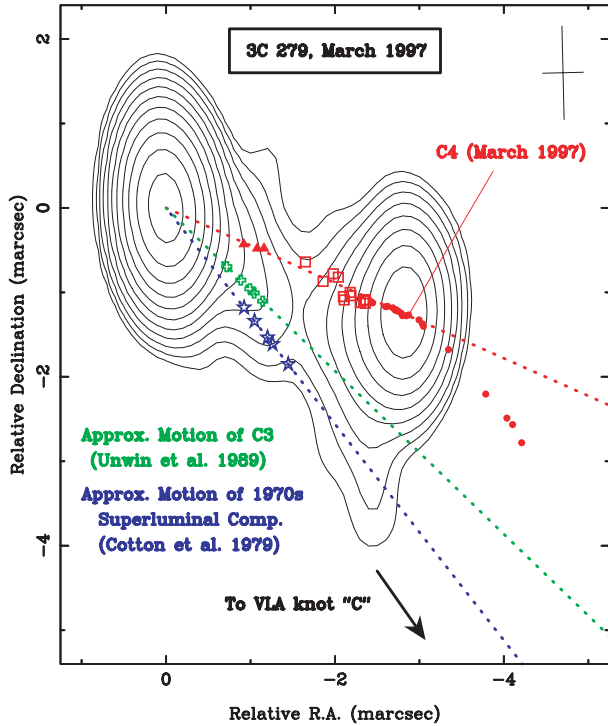


FIG. 1.—A $\lambda = 2$ cm, VLBA image of 3C 279 in 1997 March. The contours begin at 10 mJy beam^{-1} and increase in powers of 2. The cross in the northeast corner of the map depicts the FWHM dimensions of the restoring beam. Overlaid on this image in red are component positions for C4. The filled triangles are 11 GHz data from Carrara et al. (1993), the open squares are 22 GHz/43 GHz data from Wehrle et al. (2001; pre-1995.5), and the filled circles are measured from 2 cm VLBA data taken from the period 1995.5 to 2002.9. The blue open stars and the green open crosses indicate the approximate locations measured for the 1970s superluminal component and component C3, respectively (distances and position angle taken from Cotton et al. 1979 and Unwin et al. 1989). The red, green, and blue dotted lines mark the -114° , -134° , and -142° position angles, respectively.

parsec-scale jet monitoring project (Homan et al. 2001, 2002; R. Ojha et al. 2003, in preparation) that 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 two- or three-point components to the core region and a single elliptical Gaussian to C4. We have averaged the values obtained by these two approaches and have plotted the mean position in Figures 1 and 2. The core is assumed to be stationary, and the positions of C4 are taken relative to the core.

Figure 1 shows an image of 3C 279 from our 1997 March observations. Superposed on this image is the position of component C4 from each of the 19 epochs we compiled. We have also plotted 22 GHz/43 GHz data from Wehrle et al. (2001) up to 1995.5 and 11 GHz data from Carrara et al. (1993) to illustrate the trajectory of C4 from 1988 to the present. Approximate positions for the 1970s superluminal component and the component C3 are included on the figure for comparison.

Proper motions were computed from the 2 cm (x, y) -component positions in both the image and (u, v) -planes independently. 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, but we found that it made little difference which choice we made. The average motions we found across all of these

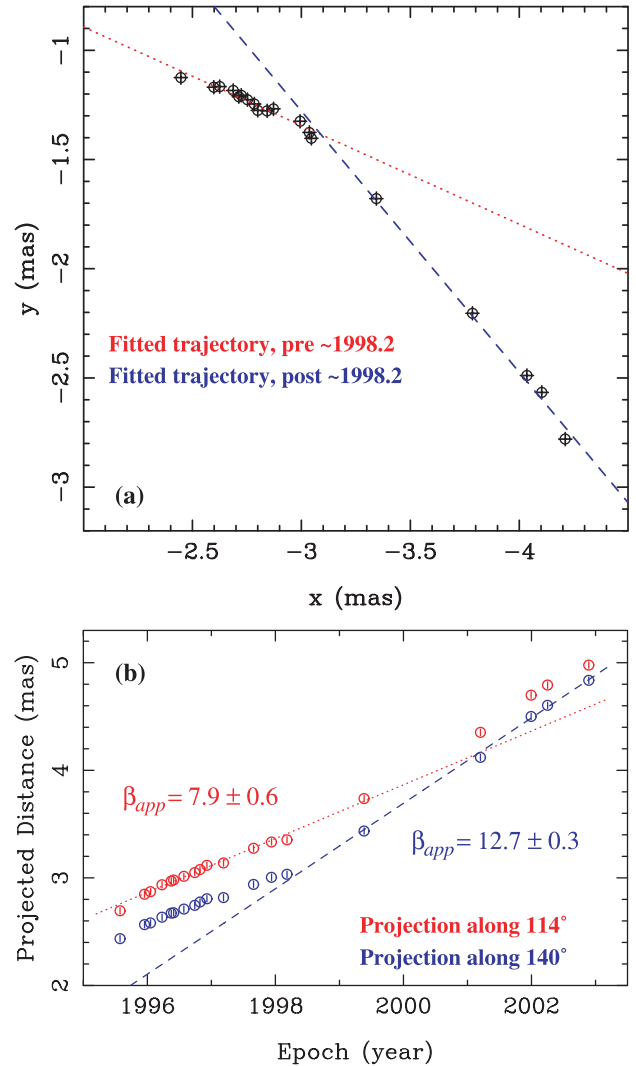


FIG. 2.—Component locations and fitted proper motions of C4 before and after the bend. Panel *a* plots the component locations and fitted motions as seen on the sky. Panel *b* plots the component distances and fitted motions vs. time. The distances in panel *b* are projected distances along the position angles corresponding to the directions of motion before and after the bend.

approaches were *prior to* ~ 1998.2 : $\mu = 0.25 \pm 0.02 \text{ mas yr}^{-1}$ ($7.9c \pm 0.6c$) along a position angle of $-114^\circ \pm 1^\circ$ and *after* ~ 1998.2 : $\mu = 0.40 \pm 0.01 \text{ mas yr}^{-1}$ ($12.7c \pm 0.3c$) along a position angle of $-140^\circ \pm 1^\circ$. These proper motions are plotted against the data in Figure 2. We estimate our typical positional uncertainty for the centroid of C4 to be 0.03 mas in both dimensions.

Figures 3*a* and 3*b* depict the change in component flux density and size along the -114° position angle, respectively, as a function of epoch. Prior to the 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 2. These events seem to come before the change in motion, suggesting that the component is already undergoing changes, likely caused by interactions with its environment, while it is still propagating along the original direction of motion. Zavala & Taylor (2001) report a change in the polarization position angle of C4 that occurred sometime between 1998.6 (Taylor 2000) and 2000.1. The polarization angle change reflects a change in magnetic field order, since Faraday rotation is small in this feature (Zavala & Taylor 2001), and provides further

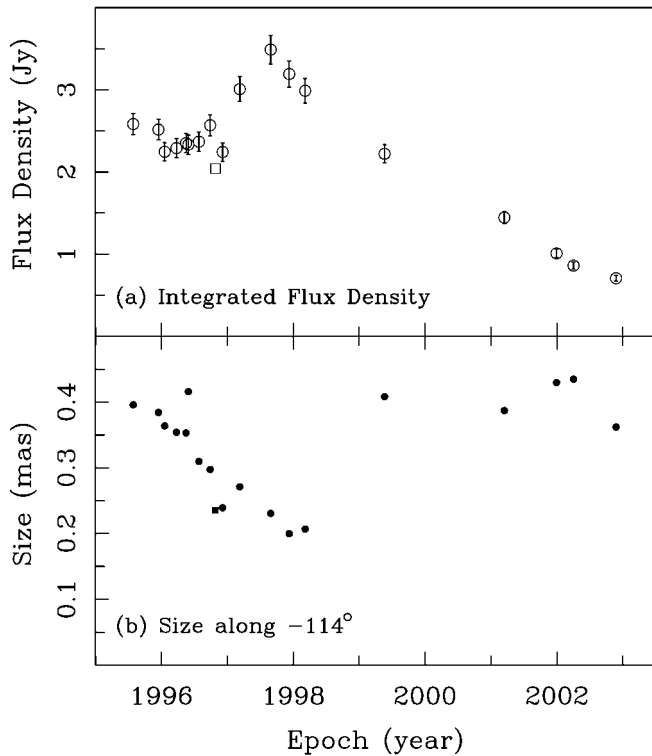


FIG. 3.—Plots of component C4’s flux density (a) and FWHM angular size projected along the -114° position angle (b). These properties are taken from our Gaussian fit to the (u, v) -plane data. The square symbols represent a poorly calibrated epoch with flux density $\sim 10\%$ low. The error bars on the flux density points are estimated at 5% of the integrated flux density in each epoch (e.g., Homan et al. 2002).

evidence that the change in trajectory is tied to internal changes in component structure.

3. ANALYSIS

Here we make a simple “billiard-ball” analysis of the component’s trajectory. We note that more complicated models are possible, perhaps involving very different pattern and flow speeds, and such models may allow a wider range of allowed γ and θ .

The apparent speed of this component has increased by more than 50%, and the trajectory on the sky has changed by 26° . According to equation (1), the apparent speed can increase either as a result of an increase in the intrinsic speed, β , or as a result of a change in angle to the line of sight. We observe a large change in projected angle on the sky; therefore, it is reasonable to assume that the angle to the line of sight has also changed. We cannot rule out an increase in β ; however, the simplest assumption consistent with our observations is that the speed of the component is constant along a bent path, and we make that assumption here.

Figure 4 plots the Doppler factor, $\delta = 1/\gamma(1 - \beta \cos \theta)$, where $\gamma = 1/(1 - \beta^2)^{1/2}$, 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 apparent speed from $8c$ to $13c$ can be accommodated by either a small increase, $\sim 1^\circ$, or a larger decrease, $\sim 6^\circ$, in the angle of the motion with respect to the line of sight.

To decide between the two possibilities of increasing or decreasing θ , we must look at the corresponding change in the

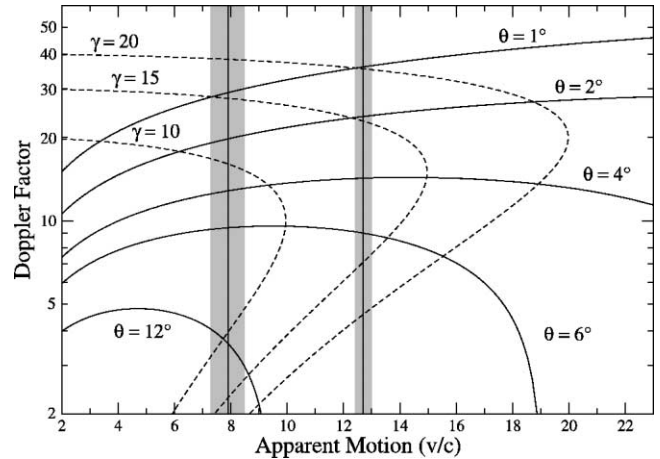


FIG. 4.—Plot of Doppler factor vs. apparent speed. The dashed contours indicate lines of constant bulk Lorentz factor, and the solid contours indicate lines of constant angle to the line of sight. The vertical lines with gray envelopes indicate the component speed before ($7.9c \pm 0.6c$) and after ($12.7c \pm 0.3c$) the bend.

Doppler factor that will scale the flux density of the jet component like $S \propto \delta^{3.5}$, appropriate for a simple discrete component with a spectral index of 0.5. For a decreasing θ (i.e., a trajectory bent toward the line of sight), the Doppler factor more than doubles between $8c$ and $13c$ 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 3a, it is clear that the flux density of the component changes by no more than a factor of 2, and after 1998 the flux density only decreases. Note that the observed compression in component size prior to the bend would be likely only to further increase the flux density, and therefore with some confidence we reject a decreasing angle to the line of sight. For increasing θ (i.e., a trajectory bent away from the line of sight), the situation is much better since 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 2, somewhat more than we actually observe but not unreasonably so.

Considering the complex nature of the light curve that is influenced not only by Doppler beaming but also by the observed compression of the component prior to the bend and expansion after the bend, we do not place strict limits here on how the Doppler factor has decreased after the bend. While the $\gamma = 15$ curve seems to provide a reasonable lower bound on C4’s Lorentz factor, we note that the Lorentz factor could be much larger and still be consistent with our observations.

From this analysis, assuming fixed component speed, we estimate $\gamma \gtrsim 15$ with an initial angle to the line of sight of $\theta \lesssim 1^\circ$ increasing at the bend to become $\theta \lesssim 2^\circ$. The bend in the plane of the sky appears to be 26° ; however, deprojected, this bend is only $\sim 26^\circ \sin \theta \sim 0.5^\circ - 1^\circ$, consistent with the required bend along the line of sight.

4. DISCUSSION

4.1. The Nature of Component C4

In the above analysis, we have taken a very simple billiard-ball model of the motion of component C4, in which C4 undergoes a sudden change in trajectory sometime during 1998. With a major axis size (FWHM) of $\lesssim 10$ lt-yr (0.5 mas) and a Doppler factor greater than 20, it is not unreasonable that C4 could have changed its trajectory in less than a year in our frame, and while this simple model fits our data quite well, a

more detailed analysis of the trajectory is desirable. Unfortunately, we are limited in this by a lack of good sampling in the period 1998–2000. An additional problem for more detailed analysis of the trajectory is that C4 is an extended region, and we are only tracking its centroid. In reality, C4 may be a complex shocked region with a strong leading edge and trailing shocks, and small changes in its centroid may not reflect true kinematical changes. In this light, we believe our simple approach is a conservative one that leads to a consistent picture of the jet kinematics.

4.2. 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 $\delta \gtrsim 28$ prior to the change in trajectory and $\delta \gtrsim 23$ after the change. These values are consistent with Piner et al. (2003), who use an inverse Compton calculation to estimate an average lower limit for the Doppler factor of C4, $\delta > 21$, prior to the change in direction.

It is interesting to compare our values with the completely independent estimate of the Doppler factor made by Homan & Wardle (2000), assuming equipartition between the radiating particles and the magnetic field. They observed a spectral turnover at 6 GHz for C4 in epoch 1997.94, just before the change in trajectory described here. They used the spectrum and resolved angular size of C4 to calculate the Doppler factor: $\delta = 18^{+6}_{-3}(\eta/\Upsilon)^{1/7}$, where η is the ratio of energy in the magnetic field to energy in the radiating particles ($\eta = U_B/U_p$) and where $\Upsilon \leq 1$ is the fraction of the volume filled with radiating plasma.⁷ Agreement between these two independent determinations of the Doppler factor of component C4 requires $\eta/\Upsilon \gtrsim 1$, implying that the energy in the radiating particles cannot greatly exceed the energy in the magnetic field unless the volume filling factor is very much less than unity.

4.3. What Caused the Bend?

We argue above that C4 was interacting with its environment prior to the change in trajectory, resulting in decreased angular size along the -114° position angle and increased flux density.

⁷ We adjusted Homan & Wardle's result for our choice of cosmology and inserted the dependence on Υ .

It seems likely, 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 superluminal component detected in 1971. It is important to stress that while the trajectory of C4 is *parallel* to that of the older component, C4 is not following the actual path of that component (see Fig. 1). The new trajectory for C4 not only has a very similar speed and direction as the 1970s superluminal feature, but it is also in the direction of the larger scale structure as seen in the 1.6 GHz VLBA maps made by Piner et al. (2000).

We suggest 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 is unclear; however, it is interesting to note that (1) the apparent collimation event occurred at a deprojected distance from the nucleus of $\gtrsim 1$ kpc, and (2) the jet is still highly relativistic, with $\gamma \gtrsim 15$, on these scales.

Abraham & Carrara (1998) discuss a precessing jet model for 3C 279 to explain the different apparent speeds and position angles of the VLBI components appearing prior to 1990. Wehrle et al. (2001) confirm the presence of different apparent speeds and position angles in the jet, even in newer components originating after C4, although their measurements do not agree with the extrapolated predictions of the Abraham & Carrara model. The concordance of the new speed for C4 with that of the 1970s component adds weight to the idea that jet components may all have intrinsically similar Lorentz factors but slightly different angles of ejection. If some sort of precession model is used to interpret the data, Wehrle et al. comment that it is difficult to understand how the range of ejection angles from -114° to -142° can be consistent with the narrow range of angles observed in the larger scale VLBA and VLA structure. Perhaps we have seen the answer here in the form of jet collimation that occurs at ~ 1 kpc or more.

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