The long-term evolution of the parsec scale jet of the quasar 3C 345

F. K. Schinzel, A. P. Lobanov, and J. A. Zensus
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
E-mail: frank@schinzels.de

Abstract. The quasar 3C 345 is one of the best examples of an active galactic nucleus (AGN) showing structural and flux variability on parsec scales around a compact unresolved radio core. Over the past 30 years, it has been followed up closely from radio to gamma-ray wavebands with a special focus on very long baseline interferometry (VLBI) observations in the range of 1–100 GHz. The complex parsec-scale jet of 3C 345 exemplifies an archetypical ‘superluminal’ jet with an apparent helical morphology. Here we present first results from a study of the long-term jet evolution, especially focusing on the evolution of trajectories, kinematics, and emission in more than 20 enhanced emission regions embedded in the jet. A "closeup" on physical properties of individual features implies that the outer jet is most likely dominated by Kelvin-Helmholtz instability. Studies of general trends in properties of those features provide certain evidence for their apparent trajectories to result from an underlying (slowly evolving) pattern lit up by passages of plasma condensations ejected during the nuclear flares. The long-term evolution of this pattern indicates its possible relation either to the elliptical mode of Kelvin-Helmholtz instability or precession of the jet direction.

1. Introduction

The archetypical quasar 3C 345 is one of the best studied “superluminal” radio source, with its parsec-scale radio emission monitored for over 30 years, in particular with very long baseline interferometry (VLBI). On parsec scales, the jet of 3C 345 exhibits a remarkably complex and a highly variable structure around a compact unresolved radio core. At high angular resolution, the radio emission of 3C 345 has been closely monitored since 1979 and it was among the first four quasars claimed to exhibit superluminal motion (cf. [1, 2, 3, 4, 5, 6, 7, 8]). Figure 1 shows a stacked image of all VLBI observations at 15.4 GHz conducted by NRAO’s Very Long Baseline Array between 1994 and 2010 (98 epochs). It shows that the jet of 3C 345 is highly collimated, with an initial direction of the flow in Eastern direction and turning northward at a distance of ~5 mas from the core. At a redshift of $z = 0.5928$ [9], 1 mas corresponds to 6.64 pc (~76 pc in the source frame) and a proper motion scale of 1 mas year$^{-1}$ corresponding to 34.5 c.

An unprecedented database of high angular resolution observations of 3C 345 was established covering a frequency range from 1 – 43 GHz and a time range of 31 years (1979 – 2010). This database comprises a total of 319 observations and combines the data of VLBI observations from the days of the US VLBI network up to the construction and operation of the VLBA. To interpret the data, the method of fitting the observed visibility data with a model (model fitting) was used, implemented in the software package “Difmap” [10]. This method provides a parametric description of the observed source brightness distribution. Brightness peaks in the
obtained images are represented by 2D-Gaussian components, which are Fourier transformed and fitted to the observed visibility data. Their parameters, flux density, size (full width at half maximum of the Gaussian component), position, and ellipticity are varied, minimizing the $\chi^2$ value using a least squares implementation of the maximum likelihood method [11]. The errors for modelfit parameters are estimated from the image plane, following analytical approximations with modifications to account for the strong side-lobe case inherent to VLBI observations (see [12] and references therein). Jet components are labeled following the naming scheme developed for 3C 345 in the early analysis of the Caltech group [1, 4] and continued by Lobanov [5] and Schinzel [13].

The full data-set of high resolution multi-wavelength observations of the parsec scale jet of 3C 345 is combined to study the variability of the jet structure, covering a time range of 31 years. In Section 2 we present our first results from the investigation of the jet structural variability of 3C 345 over three decades. Section 3 discusses the long-term kinematics of 18 distinct emission regions embedded in the jet. In Section 4 we summarize and draw conclusions from the results presented.

2. Structural Variability
Parametrized trajectories and observed component positions were combined to study structural variability of the parsec scale jet in 3C 345. Component angles measured at 0.5 mas radial distance from the core offer a way to represent time dependent variations of the observed trajectories of jet features. A significant change in this jet position angle (at 0.5 mas) is observed between 1995 and 2005, where the position angles changed from -120° to -70° and back to about -100° by 2010. Previous works have interpreted this trend as oscillation, fit by a sinusoidal function [8]. If this observed variation were due to a precession in the jet, a period of $\sim$14.5
years could be inferred.

However, an alternate explanation for the oscillation in the component position angle of the jet could be the existence of an underlying pattern in the jet that is lit up by passages of plasma condensations introduced at the base of the jet. The left-side plot in Figure 2 shows the 2D-trajectory of component C9. This component was first detected in October 1996 and since then has been followed by VLBI observations, with a reliable identification in a total of 157 observations so far. The overall trajectory of this feature traces the outline of the jet and is well represented by a polynomial fit, reporting an average apparent speed of \((0.381 \pm 0.034) \text{ mas year}^{-1}\) and an average direction of the motion of \((-88.6 \pm 1.8) ^\circ\). In addition, the position of C9 oscillates around this general motion in a more or less regular pattern. Such an oscillation is seen in many of the observed component trajectories.

The size of the emission region observed at 15.4 and 22.2 GHz for components C8, C9, and C10 is shown in the bottom plot in Figure 2. The sizes resemble a step-like evolution or in the cases of C8 and C9 a clear oscillation. The times at which the first two steps occur (0.4 and 1.5 mas) match the oscillation period observed in the trajectories of C8, C9 (Figure 2 top), and C10. Such pattern is expected if the jet is changing its position angle to our line of sight, possibly caused by Kelvin-Helmholtz instabilities [14]. The observed size evolution resembles two threads resulting from the elliptical surface mode of a Kelvin-Helmholtz instability. During maxima, the threads are apart and a double humped (edge brightened) transverse profile of the jet at this position is expected, during minima the threads overlap (in projection) leading to a single peaked transverse jet profile, which is indicated through inlets in the right-hand plot in Figure 2. With this interpretation the observed oscillation in the jet position angle measured at constant distance in the jet, discussed above, is a consequence of the rotation of this Kelvin-Helmholtz instability induced pattern and a possible time evolution of the instability modes.

3. Long-term Kinematics

Polynomial fits to the trajectories of individual jet components provide not only information about the temporal evolution of the general jet flow, but also give insights into the actual dynamics of each of the superluminal features.

The values for the apparent speeds are directly inferred from the polynomial fits to the component trajectories. Physical parameters like the Doppler factor, Lorentz factor, and viewing angle were determined under the assumption of dominating radiative losses (cf. [15]) and the presence of optically thin shocked gas. This requires the determination of the flux variability time scale. The flux variability time scale is the ratio of the measured maximum component flux density to the minimum component flux density. The time of the minimum component flux density is selected to maximize the absolute value of the time derivative of the flux density variation. This flux variability time scale was determined from 15 GHz observations only. Thus, the obtained average kinematic parameters, derived from the trajectories using the flux variability timescale, provide median values for the apparent speed of 12.5c, Lorentz factor 14.1, Doppler factor 15.6, and viewing angle of 3.8°. Figure 3 provides an overview of the distribution for each of these parameters.

The evident spread in the observed apparent speeds shown in Figure 3 indicates a wide range of observed component speeds that can be explained by non-constant speeds. The fit to the observed trajectories of most components requires second order polynomials in at least one direction. With the parametrized description of the general component motion, it is possible to reconstruct the intrinsic motion pattern in the source frame. In order to do so, at first we assumed a constant viewing angle. This leads for most of the components to a dramatic increase in the required Lorentz factor and in some cases leave the parameter space beyond which no valid solutions are found. For accelerating components the assumption of constant viewing
Figure 2. top: Two-dimensional trajectory of component C9. The thick black-line is reconstructed from a polynomial fit in $x$ and $y$ direction. White circles are spaced at intervals of one year. Note the oscillating pattern of the component evolution. bottom: Component size evolution (15.4 and 22.2 GHz). Predicted transverse brightness profiles induced by Kelvin-Helmholtz instability are indicated by inlets, denoting the expected shape.
Figure 3. Distribution of average kinematic parameters, derived from the trajectories using the flux density decay timescale. The top left panel shows the distribution of the apparent component speeds, the top right panel shows the distribution of the Lorentz factors, the bottom left panel the distribution of the Doppler factors, and the bottom right panel the distribution of the viewing angles. The median values for the respective panels are 12.5 c, 14.1, 15.6, 3.8°.

angle seems too simple. In a second attempt we investigated the more realistic possibility of a curved jet, fixing the Lorentz factor to a constant value. For slow jet components this yields unrealistically small viewing angles, also the distances jet components travel in the source frame are on the order of hundreds of pc. Finally, a combination of a curved jet in combination with a varying Lorentz factor yields satisfying results. The required change in the Lorentz factor is relatively large, but remains in a plausible range of 4 – 24, whereas the viewing angles range between 2 and 10° and the distances traveled in the source frame are on the order of 2 – 5 pc. Altogether, it appears that the combination of acceleration and viewing angle change produces the best results and provides a satisfactory interpretation of the observed component motion.

4. Summary
A compilation of over thirty years of VLBI observations of the quasar 3C 345 provides us with new insights into the long-term properties of its parsec-scale jet. A first systematic analysis of an unprecedented database of jet kinematics for a simple object was presented. This data-set revealed a highly collimated and stable outflow over a period of over three decades, supporting a slow sheath/fast spine jet flow model, providing the conditions for Kelvin-Helmholtz instabilities. Standing oscillating patterns are observed in component motions and size evolution. The pattern resembles small changes in the viewing angle and a rotation of the internal structure of the jet. This supports the interpretation of elliptical surface modes from K-H instabilities being imprinted on the observed jet. We have found the observed apparent speeds are not constant. From the investigation of different scenarios we conclude that two effects acting together are able to reproduce the observed variability in speeds. To the one hand a change in the jet viewing angle leads to a change in observed speeds, on the other hand an intrinsic acceleration of the jet flow over parsec-scales is required.
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