Detecting supermassive binary black holes with VLBI - discovery of a ring-structure in 3C454.3

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Abstract. We report the detection of the first VLBI ring-structure around the core of a quasar - 3C454.3. This ring-structure starts being visible in VLBI maps around 1996. It expands with an apparent velocity between 0.11±0.01mas/yr and 0.18±0.01mas/yr and dominates the pc-scale structure for at least 14 years. This is the result of a re-analysis of 41 VLBA data sets at six different radio frequencies observed between 1995.57 and 2011.48. We observe a correlation between radio flaring, flux-density variability, a ring-structure and kinematic properties of the jet. Taken together, it is tempting to see a causal connection and to explain all of this geometrically. The kinematic changes as well as the changes in the flaring characteristics might be caused by a change of the angle to the line of sight towards the observer. This behaviour resembles our findings for 0735+178 - with 3C454.3 being the second AGN to reveal kinematic mode changes. These mode changes could be explained by the presence of a supermassive binary black hole. 3C454.3 had been modelled as a binary black hole before.

1. Introduction

3C 454.3 is a 16th magnitude quasar at a redshift of \( z = 0.859 \). It belongs to the class of optically violent variable sources. The source has been monitored with telescopes from the radio to the TeV-regime in order to unravel the origin of the high energetic radiation detected with the FERMI satellite (Tosti et al. 2008). For some time the source was the brightest gamma-ray emitting AGN in the sky as observed by FERMI.

The radio morphology has been studied and monitored within many VLBI observations. In the cm-regime VLBI observations were performed by Moellenbrock et al. (1996). The source has been observed within the VSOP prelaunch survey (Fomalont et al. 2000). It is being monitored within the MOJAVE/2cm survey (Lister et al., 2005; Homan et al. 2006) and has been studied at higher frequencies by Lonsdale et al. (1998), Rantakyro et al. (1998), Lobanov et al. (2000), Marscher et al. (2002), and Jorstad et al. (2010). The connection between mm-continuum variations and the VLBI structure has been investigated by Savolainen et al. (2002). The polarimetry at 43 GHz was studied by Kemball et al. (1996). A detailed analysis of
component motion in the pc-scale jet of this source has been performed by Pauliny-Toth et al. (1987). In particular, the observations and analysis of early VLBI observations performed (e.g., Pauliny-Toth et al. 1987) revealed some peculiarities which seem to be unique in this source as opposed to typical "superluminals". These authors report on the detection of structural changes following a flux-density outburst which are unlike those which have been observed in the ‘classical’ superluminal sources at that time.

Qian et al. (2007) showed that the long-term radio-variability at 4.8 and 8 GHz can be explained with a binary black hole model.

2. Observations

The multi-wavelength flux-density output of this source is peculiar, and so is the VLBI structure. In order to understand the physical origin of the peculiarities, we studied in detail the pc-scale morphology and its evolution over roughly 15 years at several radio frequencies. In addition, we collected light-curve information from the radio, the optical, and X-ray wavebands. By studying not only the morphology but also the emission processes we hope to put the pieces together.

We expect that all the different properties taken together form a puzzle which - only when as complete as possible - can tell about the physical origin of the many enigmas in this source which at first glance seem to be unrelated.

It turned out that the analysis of the pc-scale jet and multi-wavelength emission reveal even more so far unknown properties of this source.

We (re-)analyzed 32 VLBA observations (between 1995.57 and 2011.48) observed at 15 GHz from the MOJAVE/2cm survey and derived the parameters of the observed VLBI structure. In addition, we investigated VLBA observations obtained at 5.0, 8.3, 15.3, 22.2, 43.1 and 86.2 GHz on May, 19, 2005. Three 43 GHz VLBA observations from March 2001 and May and October 2005 have also been investigated with regard to the spectral properties. We fitted the components of the VLBI structure with Gaussian components. We analyzed the kinematic properties of the pc-scale jet components with regard to the flaring states. We studied the properties of the lightcurves obtained in the radio (4.8, 8.0, 14.5, 22 and 37 GHz), optical (R- and B-band), and X-rays and searched for correlations between the flaring properties and the VLBI structure of the source.

3. Results

We confirm the results concerning the general VLBI structure of 3C 454.3 by Pauliny-Toth et al. (1987). The source shows a core-jet structure with a jet extending about 10 mas from the core with an estimated overall position angle of ~ -50°. Embedded in the jet are several features. Despite the general agreement with earlier studies, the source structure in the epochs analyzed here differs significantly from previous studies when investigated in more detail.

3.1. Detection of a ring-structure

In the time covered by the observations, the structure consists of three substructures: the core (K), the inner jet components (A, B, C), an expanding ring-like structure (R₀, R₁, R₂, R₃, R₄, see Fig. 1) and the outer jet components (Y, Z) at a distance of 8–10 mas from the core. To determine the individual motion of these components, we show in Fig.3 the core separation as a function of time (bottom). Fig.3 (middle) shows the position angle evolution of these components with time. Fig.3 (top) shows the flux-density evolution with time. The different parts of the jet reveal significantly different kinematic properties. Outer jet components separate from the core and are known from earlier observations. Their positions with regard to the position angle are stable. The components building the ring are shown in Fig.2. We detect a ring-like structure around the pc-scale core. To our knowledge, this is the first source for which such a ring-like
structure has been detected. The ring-like structure expands and increases in radius between March 2003 and 2010. To measure the apparent velocity of this expansion we fitted a linear regression to each ring-component. The estimated velocities range between $0.11 \pm 0.02$ mas/yr ($c$) and $0.23 \pm 0.03$ mas/yr ($c$). Thus, the ring-like emitting region must have been ejected from the core region before 1996 when it becomes visible in the VLBI maps.

**Figure 1.** Two maps with the Gaussian model fit components superimposed. A circle has been drawn to delineate the apparent ring-like structure.

**Figure 2.** Trajectories of the identified Gaussian components for the extended ring-like structure. The size of each symbol is proportional to the flux density of the component.
3.2. Unusual mode change in jet kinematics

The inner jet region consists of the core (K) and - for the time between 1995 and 2008 - the two components A and B. Between 1995 and 2005 these two components do hardly show any motion with regard to the core (see Fig. 3, left at bottom). In addition, no new component ejections can be detected within this 10 year period. Thus in contrast to typical quasars, this source reveals an unexpected behaviour:

- apparent subluminal motion of two jet components in the vicinity of the core between 1995 and 2005
- no component ejections between 1995 and 2005

The core of 3C 454.3 shows a rapid flaring starting around 2005. At the same time, the 2 inner components (A, B) start moving away from the core with apparent superluminal velocities. After 2008, two new components are detected with VLBI and must have been ejected from the core earlier: component C and D. They separate from the core with apparent superluminal velocities. We thus observe two different kinematic modes for component motion in this source: until 2005 two components remain almost stationary with regard to the core. From 2005 on, the components move with apparent superluminal speeds.

![Figure 3. Flux, position angle and core separation as a function of time for the identified components.]

4. Flux-density evolution

The radio flux-density of 3C 454.3 is known to be highly variable across the electromagnetic spectrum. In Fig.4 we show the single-dish flux-density evolution as monitored within the...
UMRAO monitoring program (4.8, 8.0, 14.5 GHz) and at two additional radio frequencies (22 and 37 GHz). The most prominent variability seems to occur simultaneously at the three frequencies. The first hint for a ring-structure has been seen in VLBI observations at 15 GHz around 1996. From this time onwards the ring-structure expands and becomes more clearly visible. It is likely that this evolving ring-structure could be related with the major radio flare seen in Fig.4 around 1995.

![Figure 4](image.png)

**Figure 4.** Historical emission behaviour of 3C 454.3 in various radio and optical band. In the top panel, the radio light-curves of 5 (red), 8 (blue), 15 (green), 22 (brown) and 37 GHz (violet) flux densities are presented. In the bottom panel, the R-band light curve (red) starting from 1990 has been complemented with historical B-band data (blue) before that date, shifted by a colour index $B - R = 1.0$, which is appropriate for intermediate-faint states. The grey shaded region indicates the approximate time of the ejection for the ring-like feature.

5. Discussion

The here reported detection of a ring-like structure around the core of 3C454.3 is a novelty in VLBI observations of AGN. The ring-like structure expands and increases in radius between 1996 and 2010 when it seems to become fainter. The estimated velocities range between $0.11 \pm 0.02$ mas/yr (c) and $0.23 \pm 0.03$ mas/yr (c). Thus, the emission of this ring might have been ejected from the core region before 1996 and might be correlated with the major flare around 1995. Based on the spectral properties of this feature it can be ruled out that the object results from a supernova explosion in the central region of 3C454.3. An Einstein ring with a dark matter component can also be ruled out due to the time scales, sizes, and spectral properties of this structure. The remaining explanations of this ring-structure are:

- the angle to the line of sight changes - the jet turns towards us, most likely due to precession. The cause of the precession can be a binary black hole at the centre of 3C454.3. This
could lead to a brightening of different regions of jet.

- extended jet region becomes visible due to shock propagation
- a jet from another (second) black hole becomes visible for a short period of time
- a combination of a changing angle to the line of sight and shock propagation

The preferred explanation of the authors is a changing angle to the line of sight due to precession. Since a binary black hole model had already been proposed to explain the observed variability in the radio lightcurves of this source (Qian et al. 2007) the observed ring structure could be the result of changed beaming properties of the source. This scenario could also explain the different variability properties. We would thus observe a precessing jet in this source turning towards us and revealing and allowing a deeper view into the inner core regions. By monitoring the VLBI and lightcurve properties of this source it should be possible to determine the timescales of the precession and deduce the parameters of the binary black hole system.

5.1. Kinematic mode changes in the pc-scale jet

Based on the observations of Pauliny-Toth et al. (1987) the components close to the core remained - after a major radio flare in 1981 at similar core separations for some time - not showing the typical apparent superluminal motion expected for this kind of objects. These structural changes, as reported by Pauliny-Toth et al., do not appear to fit easily into the scheme of relativistic jet models. The structural variations appear to be much more complex (“superluminal brightening”). The observations show a rapid increase in size of the core region and the appearance of some features which are nearly stationary with respect to component 1, while others move with apparent velocities of 20c. The authors conclude that the most likely scenario to explain the observations is that the features in the core region may not represent discrete, physical components, but rather regions where the emission from a relativistic jet is enhanced, for example by shocks. Lind and Blandford (1985) have emphasized that the velocity of shock fronts, which might be observed as a motion of ‘components’, can be smaller than that of the underlying medium, which determines the Doppler boosting of the emission. In particular, it is possible to obtain stationary emission patterns. Following the outburst, the relativistic fluid excites shocks at progressively larger distances from the core. Near the core, the shock pattern appears stationary. A change in physical conditions at larger distances from the core produces a moving pattern and gives rise to the ‘classical’ superluminal behaviour of the outer components. We find the same “stationary behavior” for the two inner components for the time after the major radio flare in 1995. Between 1995 and 2005 this stationary behaviour remained and no component ejections were seen. The kinematic behaviour changes drastically for the inner two components from 2005 on. This coincides with the onset of a different kind of radio flaring. From 2005 onwards all components move with apparent superluminal speeds. Both events - both mode changes - occurred together with a significant radio flaring. Not only did the kinematic properties of the jet components change, but the variability properties of the lightcurve also changed. The here observed kinematic mode changes compare quite nicely with our findings for the AGN 0735+178 (Britzen et al. 2010). In this source we observed three mode changes in the kinematic properties (from stationary to apparent superluminal motion) within 30 years. These kinematic mode changes correlate with significant changes of the morphology (staircase / straight jet) and correlate as well with flarings observed in the optical light-curve.

We conclude that the physical appearance of the source changed significantly around 1995 and again 2005. Most likely one of the following scenarios can explain the severe changes in the
source:
- the conditions in the jet and/or core changed drastically
- the angle to the line of sight changed and we see now a different part of the jet and/or core region

So far it is unclear, where the true core in this source might be located and whether one of the inner jet components is the core. If the core is not the left-most component then the questions remains what is the nature of the other two bright inner components. It is clear that in this source the radio flaring is not always related to component ejections. This is in accordance with our findings for 0735+178 (Britzen et al. 2010). In addition, the kinematic mode changes between "stationary" and apparent superluminal motion seem to be a more common phenomenon than expected: 0735+178 and 3C454.3 clearly show these mode changes. It would be very important to find out whether these mode changes occur periodically in this source as seems to be the case in 0735+178. This source has been explained within a model of non-ballistic motion plus precession (Gong 2008, Britzen et al. 2010). It is very tempting to conclude that a periodic mode change might be related to a precessing system consisting of two black holes. A series of papers describing the detailed data analysis and the results of the theories applied is in preparation.

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