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III Zw 2, the first superluminal jet in a Seyfert galaxy

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Abstract. So far all relativistically boosted jets with superluminal motion have only been detected in typical radio galaxies with early type host galaxies. We have now discovered superluminal motion in the Seyfert I galaxy III Zw 2, classified as a spiral. Superluminal motion was first inferred from the spectral evolution of the source and then confirmed by VLBI observations. The lower limit for the apparent expansion speed is 1.25 ± 0.09 c. The fact that the spectral and spatial evolution are closely linked demonstrates that we are dealing with real physical expansion. Prior to this rapid expansion we have seen a period of virtually no expansion with an expansion speed less than 0.04 c. Since III Zw 2 is also part of a sample of so called radio-intermediate quasars (RIQ), it confirms earlier predictions of superluminal motion for this source, based on the argument that RIQs could be relativistically boosted jets in radio-weak quasars and Seyfert galaxies.

Key words: galaxies: active – galaxies: individual (III Zw 2) – galaxies: jets – galaxies: Seyfert –

1. Introduction

The radio properties of quasars with otherwise very similar optical properties can be markedly different. There is a clear dichotomy between radio-loud and radio-quiet quasars in optically selected samples. The radio-loudness is usually characterized by the radio-to-optical flux ratio. In the PG quasar sample, which is probably the best studied quasar sample in the radio and optical (Kellermann et al. 1989, Boroson & Green 1992), radio-loud and radio-weak quasars separate cleanly in two distinct populations (e.g. Kellermann et al. 1989).

It is known that radio-loud AGN almost never reside in late type, i.e. spiral galaxies (e.g. Kirhakos et al. 1997, Bahcall et al. 1995) whereas radio-quiet quasars appear both in spiral and in elliptical host galaxies. Furthermore, all relativistically boosted jets with superluminal motion and typical blazars have been detected in early type galaxies (e.g. Scarpa et al. 1999). It is still unclear, why AGN in spiral galaxies, at the same optical luminosity as their elliptical counterparts, should not be able to produce the powerful, relativistic jets seen in radio galaxies.

However, a few sources with intermediate radio-to-optical ratios appear to be neither radio-loud nor radio-quiet. They form a distinct subclass with very similar radio morphological and spectral properties. They all have a compact core at VLA scales and a flat and variable spectrum in common. These properties are very similar to the ones of radio cores in radio-loud quasars, but their low radio-to-optical ratio and their low extended steep-spectrum emission is atypical for radio-loud quasars. Miller et al. (1993) and Falcke et al. (1995, 1996a&b) have identified a number of these sources, called "radio-intermediate quasars" (RIQs), and suggested that they might be relativistically boosted radio-weak quasars or "radio-weak blazars". This would imply that most, if not all, radio-quiet quasars also have relativistic jets. In fact, VLBI observations of radio-quiet quasars already have shown high-brightness temperature radio cores and jets (Blundell & Beasly 1998). A crucial test of the relativistic jet hypothesis is the search for apparent superluminal motion in these sources. A prime candidate for detecting this is the brightest radio source in the RIQ sample, III Zw 2, which we discuss in this paper.

III Zw 2 (PG 0007+106, Mrk 1501, $z = 0.089$) is one of the most extremely variable radio sources and a very unusual AGN. It was discovered by Zwicky (1967), classified as a Seyfert I galaxy (e.g., Arp 1968; Khachikian & Weedman 1974; Osterbrock 1977), and later also included in the PG quasar sample (Schmidt & Green 1983). The host galaxy was classified as a spiral (e.g. Hutchings & Campbell 1983) and a spiral arm was claimed (Hutchings 1983). A disk model was later confirmed by fitting of model isophotes to near-IR images (Taylor et al. 1996).

The most interesting property of III Zw 2, however, is its extreme variability at radio and other wavelengths with at least 20-fold increases in radio flux density within

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4 years (Aller et al. 1985). The source also shows optical (Lloyd 1984) and X-ray variability (Kaastra & de Korte 1988; Pounds 1986).

III Zw 2 is a core-dominated flat-spectrum AGN with only a faint extended structure (see Unger et al. 1987). The weak extended radio emission and the host galaxy is quite typical for a Seyfert galaxy. Its [OIII] luminosity is a mere factor three brighter than that of a bright Seyfert galaxy like Mrk 3 (e.g. Alonso-Herrero et al. 1997) which explains why it has been classified as either a Seyfert galaxy or a quasar. In this luminosity region a distinction between the two may not be of much significance.

Earlier VLBI observations of the source have only shown a high-brightness temperature core (Falcke et al. 1996b, Kellermann et al. 1998) and recent Millimeter-VLBI observations by Falcke et al. (1999) just barely resolved the source into two very compact components.

Based on its average optical-to-radio ratio of ~ 200 and its radio properties, it was suggested that III Zw 2 could be a radio-intermediate quasar and the presence of superluminal motion in this source was predicted. Here we will discuss multi-epoch VLA and millimeter-VLBI observations of this source confirming this hypothesis.

2. Observations and Data Reduction

In 1997 we detected the onset of a new major radio outburst in III Zw 2 and we initiated a target of opportunity program to monitor the spectral evolution of the burst with the VLA and its structural evolution with the VLBA.

The VLA observations were made at six frequencies ranging from 1.4 GHz to 43 GHz in A, B, C and D configuration from 1998 September until now. The three epochs discussed in this paper where obtained on 1998 November 04, 1999 March 23 and 1999 July 07 in CnB, D and A configuration respectively. The source 3C48 was used as the primary flux density calibrator, and III Zw 2 was self-calibrated and mapped with the Astronomical Image Processing System (AIPS). Since the 1.4 GHz observation in March 1999 was heavily confused by the nearby sun, we estimated the flux density by interpolation between earlier and later epochs.

We observed III Zw 2 with the VLBA on 1998 February 16, 1998 June 13, 1998 September 22, 1998 December 12, and 1999 July 15 at 43 and 15 GHz. We used a total bandwidth of 64 MHz for a full 8 hour scan, except for the last observation which was a 4 hour scan. We spent three-quarters of the available observing time at 43 GHz and one quarter of it at 15 GHz. For the second epoch, we used the Effelsberg 100 m telescope in combination with the VLBA. We reduced the data using the software packages AIPS and DIFMAP (Shepherd, Pearson, & Taylor 1994). Fringes were detected in the III Zw 2 data on all baselines. We calibrated the gains using system temperature information and applied atmospheric opacity corrections. To obtain a reliable total flux estimate, amplitude gains for stations with bad weather conditions were scaled up to match the other antennas. The data were then self-calibrated, first using phase-only and later phase-amplitude self-calibration with solution intervals slowly decreasing down to one minute. A more detailed discussion of the VLA spectra and the 15 GHz VLBA-data will be presented in a forthcoming paper.

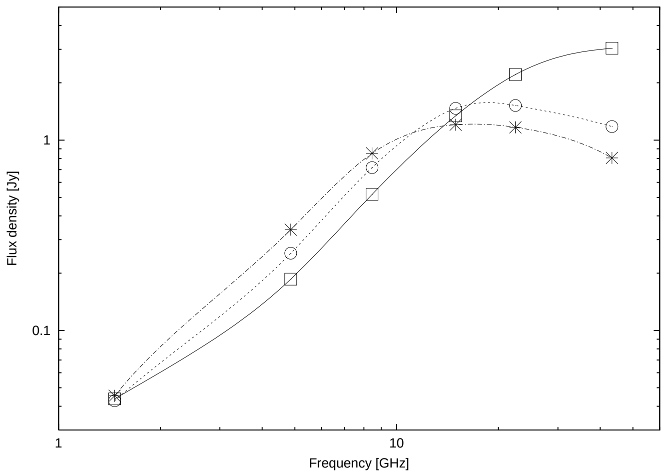

Fig. 1. VLA spectra of III Zw 2 from 1998 November (boxes), 1999 March (circles) and 1999 July (stars). The peak frequency dropped quickly within a few months from 43 GHz to 15 GHz. The lines are concatenations of the points and show the smoothness of the spectra.

3. Results

The initial spectrum of III Zw 2 from 1998 May was presented in Falcke et al. (1999). It was highly inverted at centimeter wavelengths with a spectral index of $\alpha = +1.9 \pm 0.1$ between 4.8 and 10.5 GHz. The entire outburst spectrum from 1.4 GHz to 666 GHz could basically be fitted by only two homogeneous, synchrotron components which are optically thin at high frequencies and become self-absorbed below 43 GHz. This spectral turnover frequency stayed constant until 1998 November and hence we expected no strong structural change during this time (Fig. 1).

Our first three VLBA epochs were made while the spectral peak was constant at 43 GHz. The core itself is resolved at 43 GHz at all epochs. To represent the extent of the source, the non-zero closure phases at long baselines for the 43 GHz data were fit by two point-like components. A rough estimate of the formal statistical errors of the component separation was obtained by dividing the original beam size by the post-modelfit signal-to-noise ratio (e.g. Fomalont 1999, Sect. 2.3). The errors were of the order of $1\mu as$ for the first four epochs and $10\mu as$ for the fifth epoch. Additional to this very small statistical error, there should be a larger systematic error which is difficult to quantify. To minimize this systematic error we used very similar reduction procedures for each epoch.

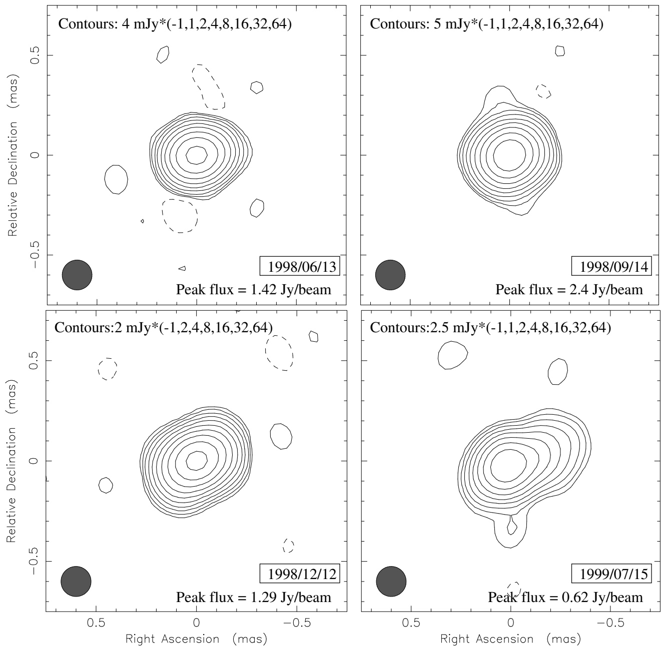

Fig. 2. Four epochs of VLBA maps of III Zw 2 at 43 GHz convolved with a superresolved beam of 150 μas. The original beam sizes were 0.29×0.12 mas at a position angle (P.A.) of $-5°$ in June 1998, 0.31×0.16 at a P.A. of $11°$ in September 1998, 0.38×0.17 at a P.A. of $-4°$ in December 1998 and 0.5×0.14 at a P.A. of $-18°$ in July 1999.

In accordance to the VLA data, the maps of the first three epochs show no structural change and the separation of the fitted components stayed constant within the statistical errors at $\sim$76$\pm$2 μas corresponding to $\sim$0.11 pc (see Table 1) for an angular size distance of 307.4 Mpc ($H_0 = 75$ km/sec/Mpc, $q_0 = 0.5$ as used in this paper).

After 1998 November, the VLA observations showed a dramatic change in the spectrum. The spectral peak dropped quickly to 15 GHz within a few months (Fig. 1). Since the peak in this source is caused by synchrotron self-absorption (Falcke et al. 1999), the fast change in peak frequency implied a similarly strong morphological change, i.e. a rapid expansion. To roughly estimate the expected expansion speed, we applied a simple equipartition jet model with a $R \propto \nu_{\rm ssa}^{-1}$ dependence (e.g. Blandford & Königl 1979; Falcke & Biermann 1995). For an initial source size $R = 0.11$ pc and a self-absorption frequency $\nu_{\rm ssa} = 43$ GHz in 1998 November, we calculate a source size of 0.32 pc for a self-absorption frequency of 15 GHz in 1999 March. Thus we predicted an apparent expansion speed of 1.9 c after the correction for cosmological time dilatation and asked for further VLBA-observations.

Indeed the fifth epoch of VLBA observations showed a dramatic structural change compared to the earlier epochs (Fig. 2). A model of at least three point-like components is required now. It was not possible to fit the closure phases with a two-component model as in the earlier epochs or to get rid of this third component during self-calibration.

Table 1. Separation D and position angle P.A. of the outermost point-like components of our model-fits to the uv-data.

Date	Total flux [Jy]	D [mas]	D [pc]	P.A.
1998/02/16	1.54 ± 0.15	0.075	0.11	$-84°$
1998/06/13	1.69 ± 0.17	0.077	0.11	$-78°$
1998/09/14	2.92 ± 0.29	0.077	0.11	$-72°$
1998/12/12	1.76 ± 0.18	0.106	0.16	$-63°$
1999/07/15	0.92 ± 0.09	0.245	0.37	$-71°$

The separation of the outer components for all five epochs is plotted in Fig. 3. While the separation at the first three epochs is consistent with an expansion speed of ≤ 0.04 c, the fifth epoch shows a rapid expansion. The apparent expansion speed between the outer components in the 4th and 5th epoch is 1.25 ± 0.09 c.

This value is only a lower limit and increases to 2.66 c if one considers the time range from December until March during which most of the spectral evolution occurred. Applying the standard equation for superluminal motion, $\beta_{\rm app} = \frac{\beta \sin\theta}{1-\beta\cos\theta}$ (e.g. Krolik 1999), to a value of $\beta_{\rm app} = 2.66$ constrains the maximal angle between the jet and the line of sight to $\theta = 41°$, since $\beta < 1$.

4. Summary & Discussion

We found a close connection between the spectral and structural evolution of the radio outburst in III Zw 2. While the self-absorption frequency remained constant, we observed no change on VLBA-scales. The excellent consistency of the relative sizes during the first three epochs on the few micro-arcsecond level demonstrates the good quality of our data. The quick drop in peak frequency after 1998 November marked the beginning of a strong structural change. The spectral peak dropped from 43 GHz to 15 GHz within a few months and the VLBA-maps show a rapid expansion with an apparent expansion velocity of 1.25 c. The fact that spectral and spatial evolution are so closely linked also demonstrates that we are dealing with real physical expansion.

With its faint extended radio structure and its spiral host galaxy III Zw 2 is clearly not a radio-loud quasar, but has properties very typical of luminous Seyfert galaxies or radio-quiet quasars. The detection of superluminal motion in this galaxy now clearly shows that we are dealing with a relativistic jet on sub-pc scales. To our knowledge this is the first detection of superluminal motion in a spiral galaxy with a Seyfert nucleus. The maximum aspect angle of 41° from the superluminal motion (see Sec. 3) is in good agreement with the orientation based unified scheme (e.g. Antonucci 1993) for AGN where Seyfert I galaxies are seen under intermediate or small aspect angles, so that the nucleus is not obscured by a dusty torus.

For the question of the nature of the radio-loud/radio-quiet dichotomy this means that radio-weak and radio-

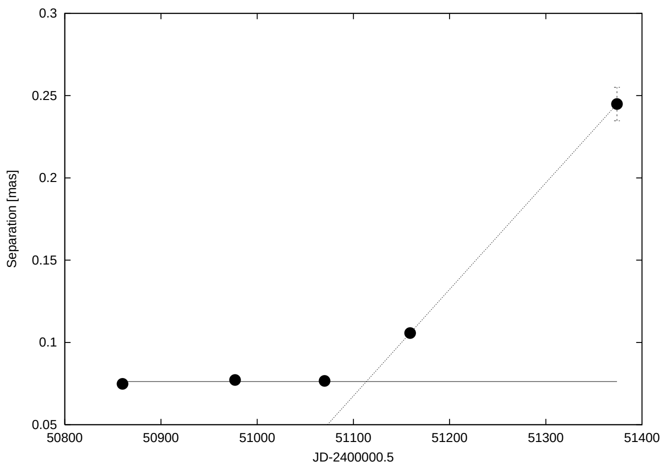

Fig. 3. Component separation from model fitting of point-like components to the closure phases and amplitudes at 43 GHz. The statistic errors for the first four epoch are smaller than the symbols and should be dominated by systematic errors. The separation of the first three epochs is consistent with an expansion speed $\leq 0.04\ c$ (solid line). The expansion speed between the fourth and fifth epoch is $1.25 \pm 0.09\ c$.

loud quasars can indeed have central engines that are in many respects very similar. Their optical properties are almost indistinguishable and both types of quasars can produce relativistic jets in their nuclei. The finding of superluminal motion supports the hypothesis of Miller et al. (1993) and Falcke et al. (1996a) that RIQs are relativistically boosted intrinsically radio-weak AGN.

While these general conclusions seem to be fairly robust, some characteristics of the outburst need to be modeled in more detail. The initial phase of the flux density rise with its millimeter-peaked spectrum and no detectable expansion perhaps has to be explained similar to the physics of Gigahertz-Peaked-Spectrum (GPS) sources, i.e. ultra-compact hotspots pumped up and powered by a jet interacting with the interstellar medium or the torus. The rapid expansion thereafter could have marked the phase where the jet breaks free and starts to propagate relativistically into a lower-density medium. Another explanation of the initial phase could be a fast jet moving through quasi-stationary components as proposed for sources like 4C 39.25 (e.g. Alberdi et al. 1993). In any case, this dramatic structural change should go together with a change of the polarization vector. This must be checked by future experiments.

The initial slow expansion has also possible implications for the interpretation of other Seyfert galaxies. For example, in observations of the Seyfert galaxies Mrk 348 and Mrk 231 (Ulvestad et al. 1999) only sub-relativistic expansion was found. Hence, one could raise the question whether the region of relativistic expansion in these two sources is at even smaller scales or whether they just happened to be in a 'slow' phase, similar to III Zw 2 early on. If true, it is still possible that Seyfert jets are launched relativistically but are slowed down and disrupted significantly already on the sub-parsec scale. Therefore it would be important to follow the spectral evolution of these sources in more detail.

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