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Multi-epoch VLBA observations of radio galaxy 0932+075: is this a compact symmetric object?

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ABSTRACT

A part of the radio structure of the galaxy 0932+075 emerged as a possible compact symmetric object (CSO) after the observation with the Very Long Baseline Array (VLBA) at 5 GHz in 1997. More than a decade later, we carried out observations at 5, 15.4, and 22.2 GHz using the VLBA to test this possibility. We report here that we have found a component whose spectrum is inverted in the whole range from 5 GHz to 22 GHz and we label it a high-frequency peaker (HFP). Using a set of 5 GHz images from two epochs separated by 11.8 years and a set of 15.4 GHz images separated by 8.2 years, we were able to examine the proper motions of the three components of the CSO candidate with respect to the HFP. We found that their displacements cannot be reconciled with the CSO paradigm. This has led to the rejection of the hypothesis that the western part of the arcsecond-scale radio structure of 0932+075 is a CSO anchored at the HFP. Consequently, the HFP cannot be labelled a core and its role in this system is unclear.

Key words. radio continuum: galaxies – galaxies: active – galaxies: individual: 0932+075

1. Introduction

The term compact symmetric object (CSO) was introduced by Readhead et al. (1994) and Wilkinson et al. (1994) to label three objects from the survey of 65 very compact radio sources observed using Very Long Baseline Interferometry (VLBI) at 5 GHz (Pearson & Readhead 1988). The authors pointed out that despite their small sizes ($\lesssim$1 kpc) CSOs were symmetric and in this regard they resembled much larger radio sources. The nature of CSOs could be explained in two ways that were immediately taken into consideration by Readhead et al. (1994): CSOs are either precursors of standard large-scale doubles or they constitute a class of short-lived objects that decay too quickly to make it possible for them to evolve from subkiloparsec-sized structures to more extended forms. Both options belong to the so-called youth scenario of compact sources. It appears that since 1994, when the CSO class was recognised, the youth scenario has been valid (see e.g. Fanti 2009, for a review).

The most straightforward proof that CSOs are young is based on the measurements of kinematic ages calculated from their lobe expansion velocities extracted from multi-epoch VLBI observations. These measurements were carried out by Owsianik & Conway (1998), Owsianik et al. (1998), Taylor et al. (2000), Marecki et al. (2003), Polatidis & Conway (2003), Gugliucci et al. (2005), Nagai et al. (2006), Polatidis (2009), and An et al. (2012). To date, the lobe expansion velocities, or at least their lower limits, have been found for 37 CSOs and so their kinematic ages, or at least their upper limits, could have been estimated. Given that for 27 of them the redshifts are known, both lobe expansion velocities and the kinematic ages of the sources can be calculated properly, i.e. with the time-dilation factor taken into account. They happen to be less than 3000 years old, but a considerable fraction – eleven CSOs out of the twenty-seven – are younger than 500 years, which is a meaningful overabundance pointed out by Gugliucci et al. (2005). This circumstance supports the conjecture that the evolution of the classic double radio sources often comes to a premature end at the CSO stage as suggested by Readhead et al. (1994).

Since CSOs are an astrophysically important albeit not very numerous class of objects, the original idea of the investigation presented here was to test whether 0932+075 (JVAS J0935+0719), a radio source identified with a galaxy at $z = 0.29$ that has not yet been recognised as a CSO in the literature, could in fact be another CSO. The scientific rationale of such an endeavour was that 0932+075 was mapped with the VLA at 8.4 GHz in the course of the Jodrell Bank-VLA Astrometric Survey (JVAS; Browne et al. 1998) and then included in JVAS although with a caveat that it was not a point-like source but an asymmetric double whose components are separated by $\sim 0\farcs4$. It was therefore selected as a gravitational lens (GL) candidate and followed up with MERLIN at 5 GHz in the course of the Cosmic Lens All-Sky Survey (CLASS; Myers et al. 2003). These observations confirmed that 0932+075 was a $0\farcs38$-wide, i.e. 1.6 kpc-wide[1] double. As such, it was still a GL candidate and was re-observed at 5 GHz with the VLBA on 02 August 1997 (epoch 1997.6). Based on the results of that observation, the possibility of the presence of a GL system appeared unlikely because the surface brightness values of the two major components were highly unequal: their ratio was 22.6:1 (Browne et al. 2003). However, a new circumstance emerged at this point and subsequently became the cornerstone of the

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[1] For redshift $z = 0.29$ and the standard cosmological parameters ($H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_{\rm m} = 0.27$, $\Omega_\Lambda = 0.73$), the angular distances pertinent to 0932+075 should be multiplied by a factor of 4.317 pc/mas to be converted to projected linear distances.

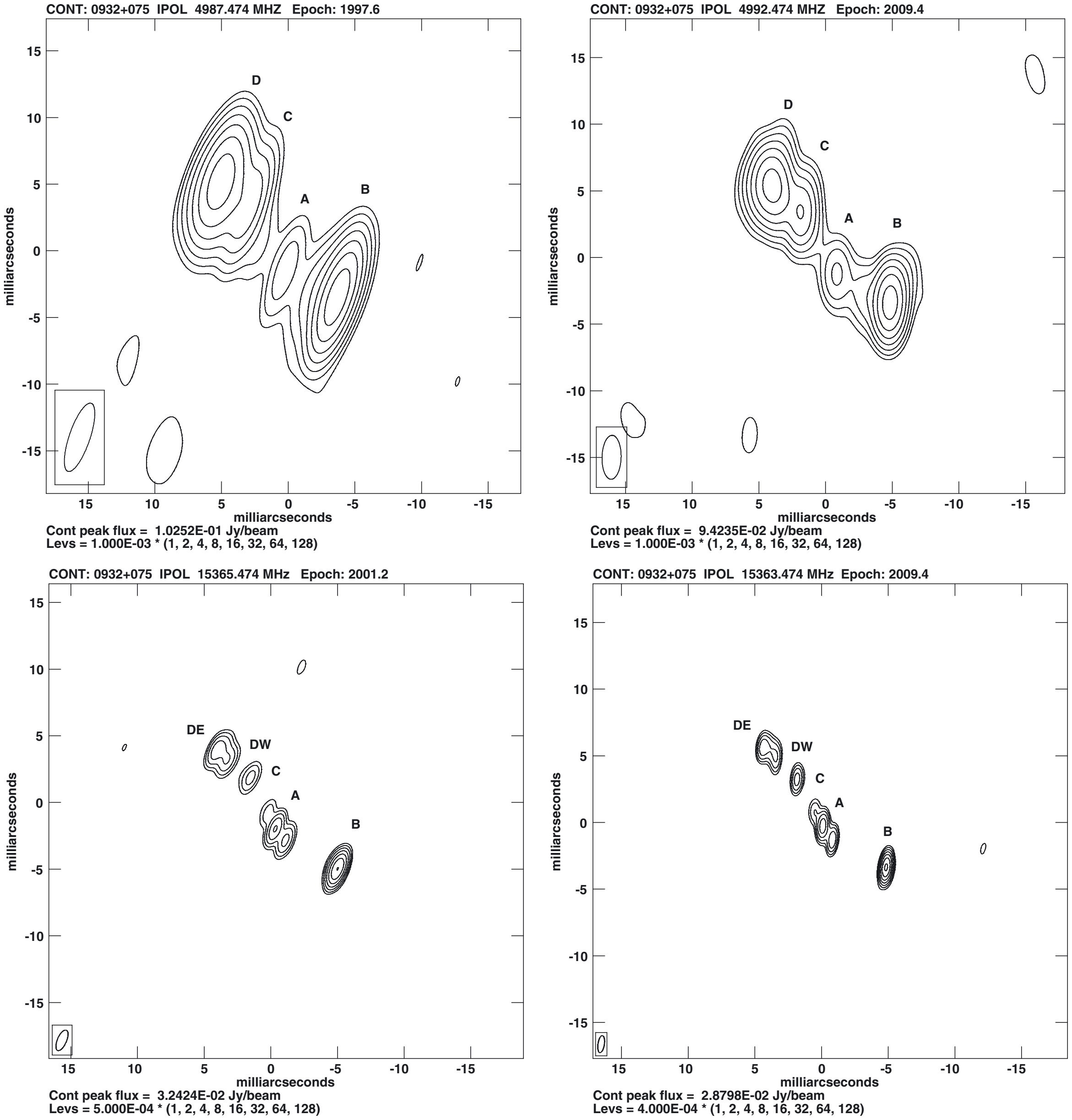

Fig. 1. Western part of 0932+075 as seen with the VLBA. In all panels, the contours are increased by a factor of 2. *Upper left*: image resulting from the 5 GHz observation carried out on 02 August 1997 and reported in Browne et al. (2003). The first contour level corresponds to 1 mJy/beam. The beam size is 5.4 × 1.6 mas at the position angle of −19°. *Upper right*: image resulting from the 5 GHz observation that we carried out on 17 May 2009. The first contour level corresponds to 1 mJy/beam. The beam size is 3.3 × 1.4 mas at the position angle of −1.6°. *Lower left*: image resulting from the observation carried out at 15.4 GHz on 22 March 2001. The first contour level corresponds to 0.4 mJy/beam. The beam size is 1.7 × 0.7 mas at the position angle −23°. *Lower right*: image resulting from the 15.4 GHz observation that we carried out on 17 May 2009. The first contour level corresponds to 0.4 mJy/beam. The beam size is 1.3 × 0.5 mas at the position angle of −8.5°.

present work. Owing to the resolution attainable with the VLBA, the detailed structure of 0932+075 was revealed (see Fig. 8 in Browne et al. 2003). In particular, the western feature shown in that image, i.e. the component that is ~23 times stronger than its eastern companion, turned out to be an almost symmetric compact double. Given its overall span (~50 pc), it was justified to tentatively label the western part of 0932+075 a CSO. Interestingly, the position angle of the potential CSO (45°) is not the same as that of the line connecting the two arcsecond-scale components (60°).

The raw observational data acquired by Browne et al. (2003) belongs to the public domain. We took this opportunity and carried out a standard reduction procedure of that data in AIPS independently. The structure of the CSO-like part that we have obtained is shown in the upper-left panel of Fig. 1. In that image, three conspicuous components: A, B, and D and at least one more, C, are visible, although C is blended with its stronger neighbouring component D. The interpretation of the three well-resolved components is not obvious, however. While the dominant features at the source's extremities are likely to be the lobes, the nature of the third one between them is unclear; it could be the core, but this is only a hint that cannot be regarded as a piece of evidence in favour of such a conjecture. Nevertheless, since the suggestion that the structure shown in the upper-left panel of Fig. 1 could be a CSO seemed reasonable, we launched an observing programme to either prove it or reject it.

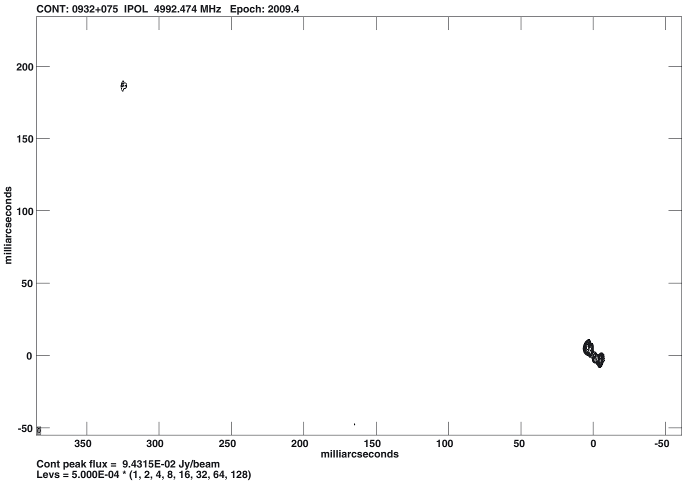

Fig. 2. Complete image of 0932+075 at 5 GHz resulting from the observation we carried out on 17 May 2009. The first contour level corresponds to 0.5 mJy/beam. Contours are increased by a factor of 2.

2. New high-resolution observations

We carried out the second-epoch observations of 0932+075 with the VLBA at two frequencies, 5 GHz and 15.4 GHz, on 17 May 2009 (epoch 2009.4), i.e. 11 years and 9.5 months after the first epoch. Sixty-four-MHz bandwidth was sampled at both frequencies (LHC polarisation). The first frequency was chosen for the sake of compatibility with the data used by Browne et al. (2003) so that possible proper motions of the components could be found, whereas the observation at the second was requested to estimate spectral indices aiming at identification of the putative core. The source 0932+075 was observed for 80 min at each frequency. No phase referencing was applied[2] as the source was strong enough to obtain the fringe residual delays and rates using its own visibilities. Standard continuum processing was applied. The resulting images are presented in Figs. 1 and 2. The 5 GHz image in Fig. 2 is a complete view of the source. It encompasses both its parts: the weak and diffuse eastern component and the dominant western one. Figure 2 is an equivalent of Fig. 8 in Browne et al. (2003); it shows exactly the same part of the sky at the same frequency, but in an 11.8-year later epoch. The western part of 0932+075 alone, as seen in epoch 2009.4, is shown in the upper-right (5 GHz) and lower-right (15.4 GHz) panels of Fig. 1.

In the epoch 2009.4 5 GHz image, the western part of 0932+075 consists of four well-resolved components. The outer two are dominating and quite symmetric – their flux densities amount to 100 and 132 mJy (see Table 1) – hence the CSO nature of the western part of 0932+075 seems to be plausible at first sight. The interpretation of the inner two components in that image is not straightforward though: either one of them is the core or neither is. The 5 GHz and 15.4 GHz flux densities of C in epoch 2009.4 are 44 mJy and 5.4 mJy, respectively (see Table 1), which means that C can be excluded as a possible core due to its very steep spectrum. Next, we investigate whether the core is associated with the component A. However, while unresolved at 5 GHz, this component reveals a triple structure at 15.4 GHz, so at that stage the location of the core remains an open matter.

Figure 3 presents a magnified view of the A-complex extracted from our 15.4 GHz image in Fig. 1 (lower-right panel). We overlaid the 5 GHz and 15.4 GHz images of the epoch 2009.4 to identify the respective components using B as a reference point because of its compactness. As a result, the positions of C at both frequencies matched well, the position of D at 5 GHz was halfway between DE and DW at 15.4 GHz, whereas the component A at 5 GHz matched neither A2 nor A3, but its position agreed with that of A1 at 15.4 GHz.

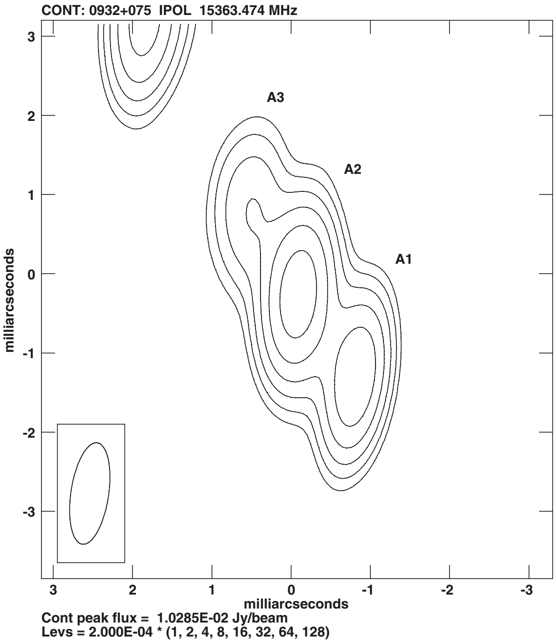

Fig. 3. Enlarged cutout from the 15.4 GHz image shown in Fig. 1 (lower-right panel) centred on the A-complex.

Table 1. Flux densities of the components of the western part of 0932+075 [mJy].

Epoch	1997.6	2009.4	2001.2	2009.4	2011.0
Component	Frequency [GHz]				
	5.0	5.0	15.4	15.4	22.2
A	7.1	11	–	–	–
A1	–	–	6.8	6.6	8.3
A2	–	–	9.3	12	31
A3	–	–	4.0	3.7	–^{a}
B	108	100	36	32	28
C	37	44	3.9	5.4	5.2
D	141	132	–	–	–
DW	–	–	–^{b}	8.2	6.4
DE	–	–	11	8.4	5.1

Notes. $^{(a)}$ Flux density of the component A3 could not be measured reliably because of blending with neighbouring component A2. $^{(b)}$ Flux density of the component DW could not be measured reliably because of blending with neighbouring component DE.

To confirm this finding quantitatively, we fitted Gaussian profiles to A and B at 5 GHz as well as to A1, A2, A3, and B at 15.4 GHz using AIPS task JMFIT. We found that the separations B–A at 5 GHz and B–A1 at 15.4 GHz were the same (4.5 mas) while the separations B–A2 and B–A3 were 5.7 mas and 6.6 mas, respectively. We assume that the uncertainties of these figures amount to 20% of the beam size[3]. Clearly then,

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[2] Browne et al. did not use phase referencing either.

[3] This is much more than the formal position errors given by JMFIT; JMFIT, however, does not take into account either the density of the $u - v$ plane coverage, or the errors of the individual visibilities. The actual errors are very difficult to estimate hence our very conservative assumption of their magnitude.

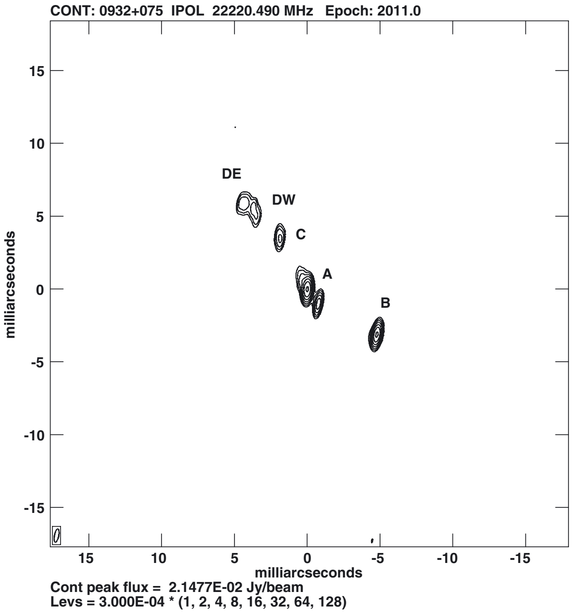

Fig. 4. Image resulting from the observation carried out at 22.2 GHz on 15 December 2010. The first contour level corresponds to 0.3 mJy/beam. The beam size is 0.9 × 0.3 mas at the position angle of −11°.

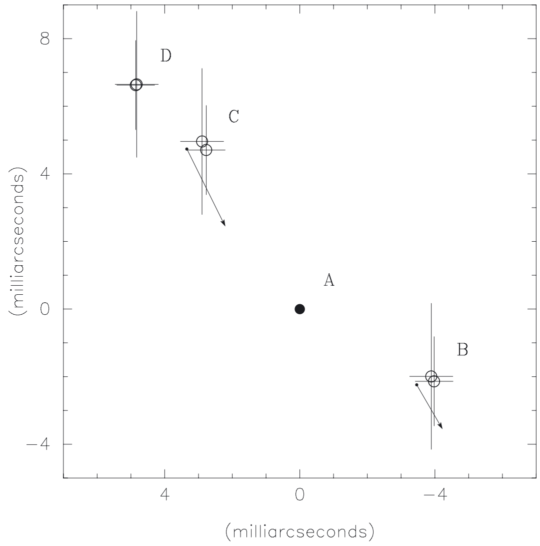

Fig. 5. Schematic diagram showing the positions of the four components seen in the 5 GHz images shown in Fig. 1. Open circles represent the positions of the centroids of B, C, and D with respect to A in the epochs 1997.6 and 2009.4. Error bars correspond to 20% of the beam sizes. The arrows indicate the direction of the components' displacements. The length of each arrow is proportional to the magnitude of the respective displacement.

component A seen at 5 GHz is not a counterpart of either A2 or A3 seen at 15.4 GHz. This immediately raises the question whether any counterpart of A2 is present in the 5 GHz map. It appears that there is no trace of such a counterpart in the 5 GHz image, although in principle it could exist because, given the separation of 1.2 mas between A2 and A1 as measured at 15.4 GHz, the resolution attained at 5 GHz is sufficient to resolve these two components at least partly. It follows that the flux density of A2 is too low at 5 GHz to make it visible hence its spectrum between 5 GHz and 15.4 GHz is surely inverted. It could thus be expected that it might also be inverted towards higher frequencies.

To test this conjecture, we observed the western part of 0932+075 with the VLBA at 22.2 GHz. The observation was carried out on 15 December 2010 (epoch 2011.0) covering a 128 MHz bandwidth (LHC polarisation). The target was observed for 220 min, again without phase referencing as the source was strong enough to obtain the fringe residual delays and rates using its own visibilities. Standard continuum processing was applied. The resulting image is shown in Fig. 4.

Finally, we searched the NRAO archive to find whether there existed any VLBA observations of 0932+075 other than those by Browne et al. (2003) and ours. We found that 0932+075 had been observed at 15.4 GHz on 22 March 2001 (epoch 2001.2), but the outcome of that observation was never published (see Acknowledgements for details). The total on-source time was ~70 min for 0932+075 at 32 MHz bandwidth with LHC polarisation only. We processed the public-domain raw data acquired in the course of that observation in a standard way. The resulting image is shown in Fig. 1 (lower-left panel).

We measured the flux densities of the components of 0932+075 in all five maps shown in Figs. 1 and 4 using AIPS task JMFIT. We assumed 5% uncertainties of these measurements. Table 1 comprises the results along with the respective epochs to clarify which measurements are quasi-simultaneous and which are not. This is essential when trying to estimate the spectral indices because of the possible variability of the source's components which, if occurring, would complicate the interpretation of the results. However, regardless of the magnitude of variability of A2 between the epochs 2009.4 and 2011.0, it clearly has an inverted spectrum between 15.4 GHz and 22 GHz hence it most likely is the core. Combined with the unmeasurable 5 GHz flux of A2, it appears that the flux density of A2 rises sharply in the whole range from 5 GHz up to 22 GHz. Owing to this type of spectrum, A2 could be classified as a high-frequency peaker (HFP; see the definition of that class in Dallacasa et al. 2000).

3. Measurements of proper motions

After we found the most likely candidate for the core, we attempted a crucial test of the CSO hypothesis: if the western part of 0932+075 was a CSO then like in most CSOs (see An et al. 2012, and references therein) we would expect expansion of the mini-lobes B and D. By the same token, the component C would be expected to travel towards the north-east, i.e. in a way analogous to D since both are on the same side of the putative core. We measured the changes of the angular distances of B, C, and D with respect to A in the 5 GHz images between the epochs 1997.6 and 2009.4 and we obtained the results which are graphically demonstrated in Fig. 5 along with the corresponding uncertainties. The separation between A and D (8.2 mas) remained nearly the same in both epochs, B moved away from A so that the angular distance between them increased from 4.4 mas to 4.5 mas, whereas C moved towards A – the separation between these two decreased from 5.7 mas to 5.5 mas. This combination of displacements cannot be reconciled with the hypothesis that the western part of 0932+075 is a CSO whose core belongs to the A-complex, because the non-core components of a CSO should either be stationary or, if not, then all of them should move away from the core.

Based on this surprising result, we rejected the hypothesis that the western part of 0932+075 is a CSO. Consequently, we claim that in the 5 GHz VLBA images (Fig. 1, upper panels) this object only mimics a CSO.

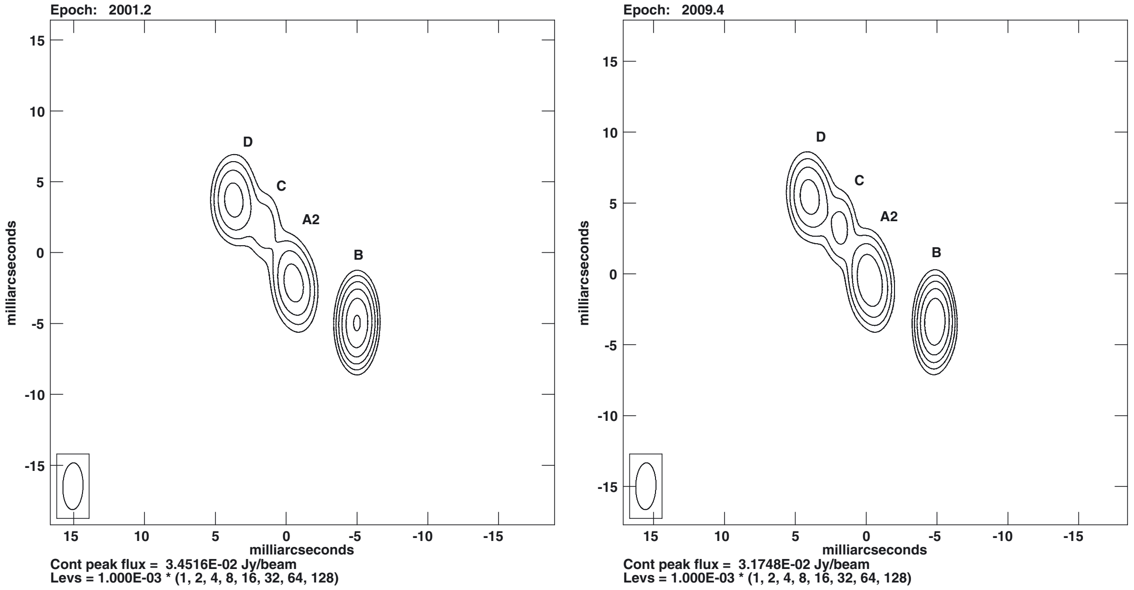

Fig. 6. 15.4 GHz images convolved with the beam of the 5 GHz observation at the epoch 2009.4. *Left*: the image based on the observation in the epoch 2001.2, *right*: the image based on the observation in the epoch 2009.4.

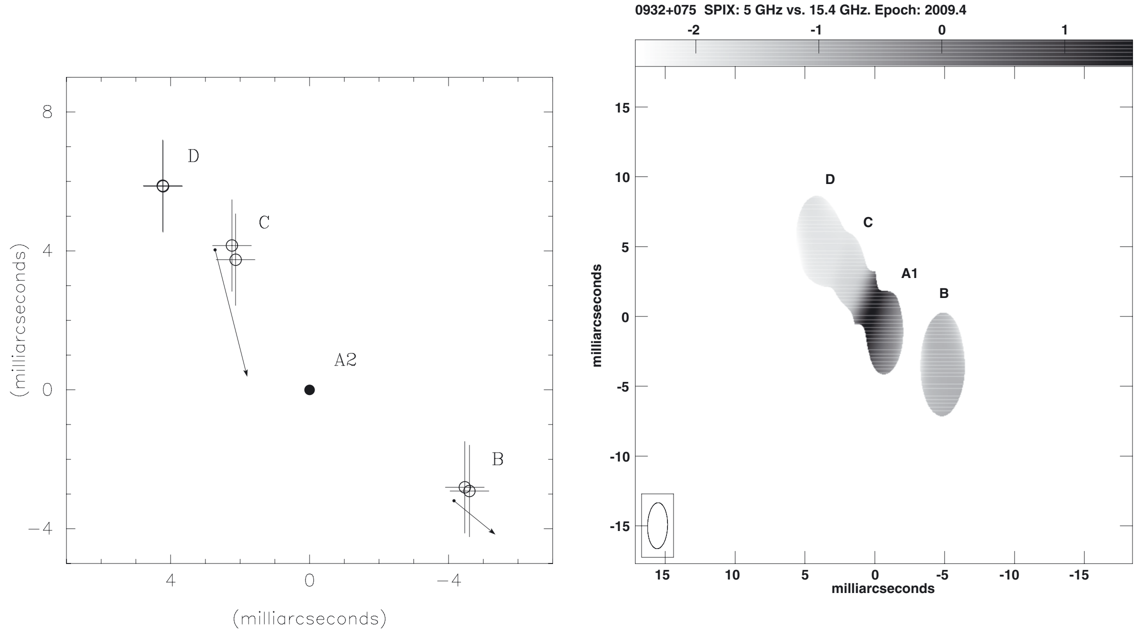

Fig. 7. *Left*: schematic diagram showing the positions of the four components seen in the 15.4 GHz images convolved with a 5 GHz beam shown in Fig. 6. Open circles represent the positions of the centroids of B, C, and D with respect to A2 in the epochs 2001.2 and 2009.4. Error bars correspond to 20% of the 5 GHz beam sizes. The arrows indicate the direction of the components' displacements. The length of each arrow is proportional to the magnitude of the respective displacement. *Right*: 5 GHz vs. 15.4 GHz spectral-index map for epoch 2009.4 prepared from the images shown in Fig. 1 (*upper-right panel*) and Fig. 6 (*right panel*).

Given that the result we obtained is non-standard and taking the opportunity that there is another pair of high-resolution observations of 0932+075, i.e. the 15.4 GHz VLBA observations of epochs 2001.2 and 2009.4 (Fig. 1, lower panels), we attempted a comparison between these two. However, to make the findings from the 15.4 GHz data compatible with the 5 GHz data described above, we convolved both 15.4 GHz images with the beam of one of the 5 GHz images, namely our image of epoch 2009.4. The resulting smeared images are shown in Fig. 6. We fitted Gaussian profiles to the features present in these maps and we measured the changes of the angular distances between component A (we note that it is now co-incident with A2) vs. components B, C, and D to find their displacements. The combined result is shown in Fig. 7 (left panel). The separation between D and A2 remains constant over time which agrees with the 5 GHz measurements. However, quantitatively it differs as it amounts to 7.2 mas, i.e. ~1 mas less than in the case of the actual 5 GHz maps because A2 in Fig. 7 (left panel) has a different position than the component A in Fig. 5 where it is coincident with A1. For the same reason, the distances A2-B in the set of maps in Fig. 6 are greater by ~1 mas than those in the true 5 GHz maps and amount to 5.3 mas and 5.4 mas in respective epochs. Furthermore, we have found that the A2-C distance has decreased between epochs 2001.2 and 2009.4 from 4.7 mas to 4.3 mas. This decrease confirms our earlier findings of the component C travelling in the opposite direction to the lobe expansion expected in the case of a CSO. Therefore, we again reached the conclusion that a CSO paradigm is not applicable to the case of 0932+075. The magnitude of that decrease is twice that measured at 5 GHz. This is somewhat uncomfortable, but tolerable given the uncertainties of all the above separations indicated by the error bars in the left panel of Fig. 7: their magnitudes are 20% of the 5 GHz beam size.

At this stage, we took the opportunity that the 15.4 GHz image of epoch 2009.4 convolved with the 5 GHz beam (Fig. 6, right panel) is ideally suited to be combined with the 5 GHz image of the same epoch (Fig. 1, upper-right panel) to calculate the spectral indices between these two. The resulting spectral-index map is shown in Fig. 7 (right panel). As can be clearly seen there, the area featured by inverted spectrum, i.e. the location of the HFP, is not coincident with the centre of the silhouette of component A1. This is in full agreement with our findings reported in Sect. 2.

Finally, we compared the two original-beam 15.4 GHz images of 0932+075. Here, the A2-B distance changed from 5.57 ± 0.60 mas to 5.68 ± 0.45 mas with the uncertainties of 20% of the 15.4 GHz beam sizes. The difference between these figures remains in agreement with that derived from 5 GHz maps and 15.4 GHz maps convolved with a 5 GHz beam. The A2-C distance has decreased from 4.29 ± 0.73 to 4.00 ± 0.55. This result is probably not as reliable as it might seem because of the noticeable departure from the Gaussian shape of C as seen in the epoch 2001.2 map (Fig. 1, lower-left panel) which causes difficulties with fitting a single Gaussian profile. Measuring the angular distance to D was problematic since it has a double structure at 15.4 GHz (as well as at 22.2 GHz). We failed to fit a Gaussian model to the component DW in the map from epoch 2001.2. Therefore, we only measured the separation A2-DE that changed from 7.31 ± 0.71 mas to 7.37 ± 0.54 mas. It follows that, while the D component as a whole remains stationary with respect to A, both at 5 GHz and 15.4 GHz, its subcomponents probably move apart. Second-epoch 22.2 GHz observations where DE and DW are only sufficiently well resolved should shed more light on this question.

4. Conclusions and future work

Using the observational data presented here, we provided the two main pieces of new evidence characterising 0932+075. First, one of the components of the milliarcsecond-scale structure of this source (A2) has a clearly inverted spectrum for frequencies up to 22 GHz. Owing to this property we label it a HFP. Second, it turns out that the western part of 0932+075 is not a CSO as the 5 GHz VLBA image of epoch 1997.6 (upper-left panel of Fig. 1) might suggest. Instead, we propose the following tentative interpretation of the milliarcsecond-scale morphology of the western part of 0932+075. What we see in the 15.4 GHz and 22.2 GHz VLBA images is a superposition of two groups of components. The first group consists of A2 and its closest neighbours A1 and A3, whereas the second group encompasses all the remaining components. This division was chosen because the second group is nearly co-linear while the A-complex is an outlier. It is not clear what kind of relationship connects the HFP to the other components of 0932+075 and whether the co-linearity of the latter is significant, but there is a hint that it might be significant given that the directions of the displacements of B and C with respect to D are roughly the same as that of the line connecting these three components (see Fig. 5). It could be thus speculated that the co-linearity is caused simply by the motion of B and C both travelling from the origin located at D. However, the weak point of this scenario is that D plays the role of a secondary core, which is doubtful because of its steep spectrum.

The main drawback of the observational material presented here is that Browne et al. did not use the phase referencing, and neither did we. The reason for this is simple: 0932+075 itself is an acknowledged phase calibrator used for interferometric observations. Since we have now discovered quite complicated displacements in its milliarcsecond-scale structure, it appears that it would have been very advantageous if the VLBI observations of 0932+075 of all epochs had been phase referenced to the same phase calibrator so that the absolute positions of the components could have been known. Unfortunately, this is not the case and we had to rely on the measurements of the relative positions as presented in Sect. 3. In addition, the two-point proper motion measurements we have carried out are not very reliable hence the results presented here should be regarded as only preliminary. Consequently, a much more thorough study based on high-resolution monitoring of 0932+075 is necessary to carry out, as accurately as possible, measurements of the proper motions of its milliarcsecond-scale components based on their absolute positions obtained from phase referencing. The new observations should be multi-frequency and quasi-simultaneous with regard to the set of frequencies at a particular epoch to find out what the exact spectral indices of each component are. Full polarisation information would also be helpful since only very few CSO jets have measurable linear polarisation, whereas in blazar jets fractional polarisation tends to increase with distance from the core.

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