

## X-shaped radio sources as parent population of core-dominated triple blazars

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There are a number of theories explaining the nature of the so-called X-shaped radio sources. According to one of them, an X-shaped source is indeed a cross whose one arm is associated with a double radio source that has changed its orientation in space, while the other arm is associated with relic lobes and its position indicates the former direction of the jets. Here, I present two new arguments in favour of this conjecture. Firstly, it is obvious that shortly after the repositioning, the pair of the new lobes must be very compact. To illustrate such a possibility, I show an EVN<sup>†</sup> image of the central component of a triple source J1625+2712. When resolved, it appears as a compact double that is not aligned with the outer double so the whole source is indeed X-shaped. Secondly, I consider the situation when one of the arms of an X-shaped source is not intrinsically short but foreshortened by projection. I show two examples of triple sources whose central component is a blazar and the span of the lobes that straddle it amounts to more than  $6 \times 10^5$  pc. An assumption that sources of this kind have one axis, and so the lobes are beamed in the same way the core is, would require unrealistically huge deprojected linear sizes. Therefore, I claim that core-dominated triples (CDT) like these two have two axes: the one pertinent to the relic lobes is not pointed towards us so they are not beamed/foreshortened, whereas the axis pertinent to the jets makes a small angle with the line of sight so that a blazar is observed. It follows that X-shaped sources must be actual crosses and they are the parent (unbeamed) population of at least some CDT blazars, particularly those with large overall sizes.

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## 1. Introduction

For decades, the “twin exhaust” model of a classical double radio source [4] along with the unification scheme in which the orientation effects play a fundamental role [19] have been used as a general theoretical framework successfully explaining the nature of an overwhelming majority of radio sources identified with active galactic nuclei (AGN). Nevertheless, it has been noticed [11] that some extragalactic radio sources can have more complicated structures. Apart from the components accounted for by the theory – the cores, the jets, and the lobes – “bridges” linking the host galaxy with the outer edges of a radio source are also evident. In [11], bridges are interpreted as a result of backflows, i.e. two streams of matter flowing back from the hotspots towards the host galaxy. Moreover, it has been claimed in [11] that when the backflowing material originating at one hotspot collides with the backflow from the opposite lobe, it may expand laterally giving rise to a thick disk located perpendicularly to the lobe axis. When viewed from the side, such a disk would be perceived as a secondary elongated structure, that, together with the primary one consisting of the lobes and bridges, would look as two arms of a cross. Three objects described there – 3C 52, 3C 136.1, and 3C 315 – clearly bore the signatures of cross-shaped (hereafter X-shaped) radio sources. It must be stressed though that in the backflow scenario, these sources are not crosses intrinsically but only apparently, hence the “X-shape effect” takes place only when the axis of the source lies in the sky plane and so the disk resulting from the clash of backflows is seen from the side.

An opposite concept that X-shaped sources *are* actual crosses is plausible but requires a completely different mechanism – the jet re-orientation. When it happens, the existing standard double-lobed structure is no longer fuelled so it becomes weak and diffuse, and its spectrum steepens owing to radiation and expansion losses, while a new double-lobed structure centred at the same host galaxy – it is oriented at an angle with regard to the other one – starts to build up. As a result, an X-shaped structure develops. The primary arm normally resembles Fanaroff–Riley type II (FR II) [6] radio source, while the secondary arm – the two halves of which are often termed “wings” – is a relic whose position indicates the former orientation of the jet. A comprehensive analysis of the properties of radio emission from several best known X-shaped sources presented in [18] lends a strong support to this interpretation.

The strengths and weaknesses of different models of X-shaped sources were critically assessed in [10]. Based on the two-frequency observations of eleven X-shaped sources carried out with the Giant Metrewave Radio Telescope (GMRT), the authors concluded that backflow as well as buoyancy and conical precession did not convincingly explain formation of X-shaped sources, thereby re-orientation of the jet axis owing to a merger appears as a plausible solution. Yet, at least one issue can hardly be reconciled with this particular interpretation – the small number of known X-shaped sources as compared to the ubiquity of mergers. That’s why the authors of [10] proposed their own concept, in which the scarcity of X-shaped sources stems from a rare putative situation when a galaxy contains two active nuclei each responsible for a pair of jets. However, there is a serious problem with this approach – it fails to explain the absence of X-shaped sources where both lobe pairs are of FR II type – see e.g. Fig. 1 in [5] – which should be quite a likely combination if we assume the presence of two independent central engines. It looks, therefore, that also this model is not satisfactory and, consequently, neither one out of the several available in the literature

to date provides a fully consistent explanation of the nature of X-shaped sources.

Does this mean that the correct theory of X-shaped sources is yet to be found? In the light of [17], probably not. Assuming that one of the existing models – a sudden flip of the jet orientation caused by a merger – is the most promising one, the authors put it under a rigorous test. Its idea is as follows. If mergers are the prime cause that eventually leads to creation of X-shaped sources then the supermassive black holes (SMBH) in the centres of their host galaxies should statistically have higher masses than central SMBHs in standard double-radio-lobed active galaxies. Also, a past merger event should be reflected in starburst history of the host galaxy. In order to test these conjectures, the SMBH masses, luminosities, starburst histories, and jet dynamic ages in a sample of 29 X-shaped galaxies selected from the list of candidates extracted from the VLA FIRST<sup>1</sup> catalogue [5] have been determined and compared with those in a control sample of 36 radio-loud active galaxies with similar redshifts and optical and radio luminosities [17].

The outcome of the test provided a strong underpinning to the hypothesis of jet re-orientation induced by a merger. The mean SMBH mass of X-shaped sources' host galaxies indeed appeared higher than that for the control sample as predicted by the model. A comparison of the starburst and dynamic ages in the galaxies hosting X-shaped sources and those in the control sample lent further support to the scenario in which the primary arm of an X-shaped source might have resulted from re-orientation of the host galaxy's SMBH [16] following the parent pair of black holes coalescence, the ultimate stage of a merger. In particular, it was showed in [16] that the orientation of a black hole spin axis would change dramatically even in a minor merger, leading to re-orientation of the coalescing SMBHs and a flip in the direction of the jets. On a basis of a thorough theoretical analysis, Liu [12] concluded that the realignment of a rotating SMBH with a misaligned accretion disk was due to the Bardeen-Petterson effect [3] and that the timescale of such a realignment was  $< 10^5$  years, which was negligible in comparison with typical lifetime of the lobes that are no longer fuelled (up to  $10^8$  years [8]). These two estimates fit well to the likely mechanism of creation of X-shaped objects. On the one hand, the realignment process is relatively quick so the new position of the jets is established early allowing the new (primary) arm to grow for sufficiently long time to attain a noticeable size, which is what we observe. On the other hand, owing to its longevity, the old (secondary) arm remains visible during all that process.

The weight of observational evidence after publication of [17] seems to favour the scenario in which merger is the prime cause triggering creation of an X-shaped source. It must be noted, however, that it has one weakness: X-shaped sources are rarely identified with mergers, albeit an impressive example of an X-shaped source associated with a merger was recently shown in [9].

## 2. In quest of concealed X-shaped sources

There is yet another important prediction of the central engine re-orientation scenario: the existence of “concealed” X-shaped sources. When the axis of the central engine changes its position (whatever the mechanism responsible for this – merger or maybe something else), the new primary arm starts “from scratch”. Therefore, if only the re-orientation is a real phenomenon then there should exist a rare subclass of sources where an event of this kind took place quite recently so that

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<sup>1</sup>*Faint Images of the Radio Sky at Twenty (Centimetres)*

the length of the newly established primary arm is so far minute compared to the length of the old, large-scale secondary arm. In practical terms, this means that a newly created X-shaped source would *not* be perceived as such because the very short primary arm would not be resolved in an image encompassing the whole source. For example, if repositioning of the central engine took place, say,  $10^5$  years ago then a new double growing at a rate of  $0.2 - 0.3c$  would attain the length of the order of only a kiloparsec. It follows that the primary arm will be embedded within a source compact enough to appear in a map of the whole radio structure as a single, point-like component straddled by large-scale double.

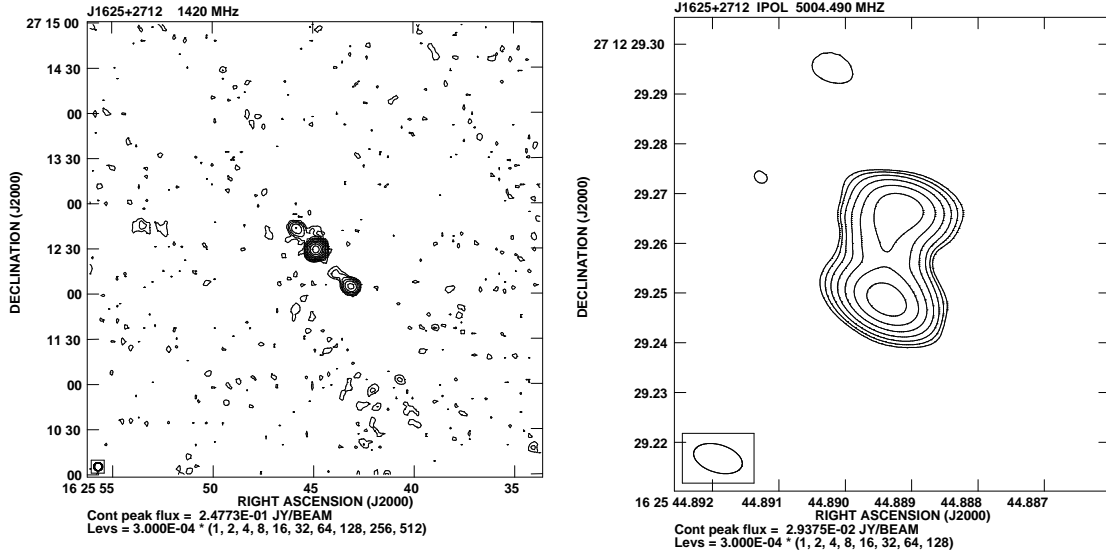
In 2004, I launched an observational project aimed at discovering of a number of exotic classes of radio sources including the one characterised above. The idea was as follows. Clearly, there exist radio sources somewhat similar to FR II, where the FR II-like lobes straddle a central component which is by far the brightest feature of the whole object. I labelled them core-dominated triple (CDT) sources. CDTs are intriguing because true FR IIs are lobe-dominated so there must be a fundamental difference between these two classes. There are three possible explanations of CDTs:

1. The “core” of a CDT is actually a compact double aligned with the large-scale (outer) double. As a whole, the object is a double-double radio source with an extreme ratio of outer/inner double linear sizes.
2. The “core” of a CDT is actually a compact double but not aligned with the large-scale double. This is a “concealed” X-shaped source shortly after repositioning of the central engine.
3. The core of a CDT is actually a radio-loud AGN like the core of a standard FR II source but its excessive brightness is a result of Doppler boosting caused by beaming. As a whole, the object is in fact a fully fledged X-shaped source where the primary arm is pointed towards the observer and so extremely foreshortened, while the secondary is not.

More than a hundred CDTs were selected from FIRST using a semi-automated procedure described in [14]. I divided the sources into two groups depending on whether the “cores” had steep or flat spectrum. Objects in the steep-spectrum group could possibly belong to the first or the second category out of the there itemised above, whereas flat-spectrum objects are likely to belong to the third category. The central component of the members of the steep-spectrum group were observed with MERLIN [14] and then, depending on their nature revealed by MERLIN, possibly followed up with the EVN. This observational campaign already brought one interesting result; it was shown in [15] that the first category of object has at least one specimen: B 0818+214. It was resolved with MERLIN at 6 cm and the EVN observations at 18 cm confirmed it was a double, not a core-jet. All in all, B 0818+214 turned out to be an extreme case of a double-double source, where the linear size of the inner double was two orders of magnitude less than the size of the outer double. Six sources observed with MERLIN had unresolved cores, though – see Table 1 in [14]. Thus, a 6-cm EVN follow-up was carried out to resolve them. In the case of J1625+2712, one of those six targets, the EVN result was very surprising.

J1625+2712 is a CDT source where, according to FIRST, the core of 261 mJy is straddled by weak lobes of 5 and 1 mJy, respectively. The spectral index of the core between 1.4 GHz and 5 GHz is  $\alpha = -0.68$  so it is clearly a steep spectrum source. The map in the left panel of Fig. 1 is a cut-out

from FIRST showing the whole J1625+2712. Not only in this image but also in MERLIN 6-cm map, the core is point-like. However, in the 6-cm EVN map, the alleged “core” has been resolved into a double where the separation of the two peaks is only 18 milliarcseconds – see the right panel of Fig. 1. The P.A. of the line connecting the maxima is  $-7^\circ 6'$ , whereas the P.A. of the large-scale structure – its angular size reaches  $53'' 5$  – is  $42^\circ$ . It follows that the misalignment between the two pairs of lobes is nearly  $50^\circ$ .



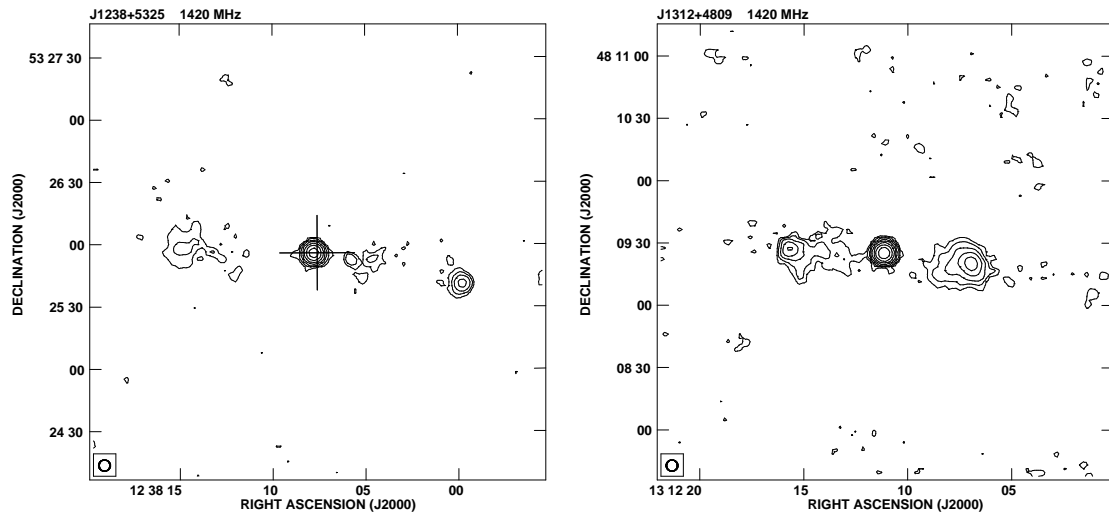
**Figure 1:** *Left:* A cut-out from FIRST centred on J1625+2712, *Right:* a 6-cm EVN image of the central component seen in the FIRST map

The most straightforward interpretation of J1625+2712 is that this is an X-shaped source, but since one arm of the cross is 3,000 times shorter than the other, the actual structure of J1625+2712 cannot be recognised in the FIRST map showing the whole radio source. Unfortunately, the redshift of J1625+2712 is not known, so we can only estimate the upper limit for the linear size<sup>2</sup> of the compact double, which is 154 pc (500 ly). Thus, I claim that J1625+2712 is a “concealed” X-shaped source observed very shortly after the repositioning of the central engine. The case of J1625+2712 supports the hypothesis that X-shaped sources are actual crosses.

### 3. Distortion of X-shaped sources caused by orientation

Because of the growing weight of evidence that X-shaped sources *are* actual crosses, it becomes more and more obvious that we should consider the impact of orientation on the perceived appearance of such sources. Plain X-shaped structure requires absence of any significant distortion caused by orientation effects, i.e. both arms of the cross must lie close to the sky plane for an X-shaped source to be observed as such. Let’s assume that in some X-shaped sources only the secondary arm lies close to the sky plane while the primary arm is oriented towards the observer.

<sup>2</sup>Based on the well-known property of the angular-size distance: the ratio of linear to angular sizes cannot exceed 8.558 pc/milliarcsecond (assuming standard cosmological parameters).



**Figure 2:** FIRST images of two CDT blazars. Contours are increased by a factor of 2; the first contour level corresponds to 0.4 mJy/beam.

In this configuration, the observed structure would consist of a beamed, Doppler-boosted base of the jet seen head-on and so perceived as a strong single component (a core), whereas the wings would appear as a diffuse double straddling that bright core. We would thus observe a CDT source with a flat-spectrum central component. When the angle between the primary arm and the line of sight is small, then, according to the unification scheme of AGNs [19], the core component would be perceived as a blazar.

If the projected span of the lobes in a CDT identified with a blazar is of the order of a significant fraction of a megaparsec, an extreme foreshortening of the whole source imposed by the presence of blazar in its centre is rather impossible, otherwise the actual size of the source would be prohibitively large. However, it is very easy to circumvent this problem – the foreshortening of the outer components of a CDT blazar does not need to be large or may even not take place at all if we assume that they correspond to the secondary arm of an X-shaped source and so they are not beamed. I thus hypothesise that X-shaped sources are the parent population of at least some CDT blazars, especially those whose overall projected linear sizes of the triple are large.

Fig. 2 presents two blazars with obvious CDT large-scale structures. Their basic parameters are shown in Table 1. As can be seen there, the overall linear sizes of the radio structures are of the order of hundreds of kiloparsecs. If one still requires that these sources are standard FR II doubles but highly foreshortened so that their cores appear as blazars [1], then the deprojected linear sizes would be at least of an order of magnitude higher. The linear size of the largest radio source known to date – a giant radio galaxy (GRG) J1420–0545 – amounts to 4.69 Mpc [13]. Although it cannot be ruled out completely that the two objects shown in Fig. 2 are in fact extremely large but highly foreshortened GRGs, my claim that the outer components of CDTs are not subject of extreme foreshortening appears as a competitive alternative.

**Table 1:** Basic parameters of CDT blazars that are likely to be X-shaped sources distorted by orientation

Name	RA	Dec	$z$	$S_{core}$	$S_{lobe1}$	$S_{lobe2}$	Linear size
J1238+5325	12 38 07.782	+53 25 55.83	0.347	43.24	8	7	663
J1312+4809	13 12 11.144	+48 09 25.22	0.715	105.70	36	21	625

Coordinates and  $S_{core}$  are from FIRST catalogue.  $S_{lobe1/2}$  have been extracted from FIRST maps using AIPS utility TVSTAT. Fluxes (at 21 cm) are in mJy. Linear sizes are in kpc. Standard values for  $H_0$ ,  $\Omega_m$ , and  $\Omega_\Lambda$  have been used to calculate the linear sizes.

The above proposal has several advantages:

1. The overall projected linear sizes of CDT blazars can be even of the order of a megaparsec simply because there is little or hardly any projection acting on the large-scale structure.
2. The reason why the outer components of a CDT blazar are diffuse is obvious: they look so because they are fading since they are no longer fuelled by the jets that are now oriented towards a completely different direction: close to the line of sight.
3. The presence of misalignments between the apparent direction of the jet in the central component of a CDT (if resolved) and that of the large-scale structure – such a phenomenon is clearly observed in blazars in general [2, 7] – is obvious, expected and even required. This is because the direction of the primary arm is close to the line of sight as posited by the blazar paradigm, but usually not identical. Therefore, apart from having a dominating radial component, this direction has also a minor tangential component. The observed positional angle of the latter, i.e. the apparent orientation of the jet on the sky plane, is random and so uncorrelated with any fixed orientation including that of the secondary arm.

#### 4. Conclusions

My preferred interpretation of the nature X-shaped sources is that they are just standard doubles that have undergone repositioning of the axis. The “wings” are relics of the former lobes. I also propose that CDTs are closely related to X-shaped sources. Two scenarios are possible: CDTs with steep-spectrum central component are those X-shaped sources that are seen shortly after the repositioning and so the newly created pair of lobes is still very compact, whereas CDTs with flat spectrum central component are typical X-shaped sources where the primary arm of the cross is beamed towards the observer. The latter scenario is particularly likely for CDTs whose central components are identified with blazars.

If the above two-part interpretation of CDTs is correct then X-shaped sources are perceived as cross-shaped simply because they *are* actual crosses, not apparent owing to a particular orientation as posited by the backflow model. Hence, the explanation presented here contradicts the backflow model and strongly underpins the AGN re-orientation scenario proposed in [16] and later elaborated in [12].

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