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X-shaped radio galaxies: their black hole masses and starburst histories

M. Mezcua[1], A. P. Lobanov[1], V. H. Chavushyan[2], and J. León-Tavares[1,2,3]

[1] Max Planck Institute for Radio Astronomy, Auf dem Hügel 69, 53121 Bonn. E-mail: mmezcua@mpifr.de
[2] Instituto Nacional de Astrofísica, Óptica y Electrónica, Apdo. Postal 51, 72000 Puebla, México
[3] Aalto University Metsähovi Radio Observatory, Metsähovintie 114, FIN-02540 Kylmälä, Finland

Abstract

A recent merger of two supermassive black holes (BH) or the presence of a second active BH in the galactic nucleus are two of the main scenarios proposed to explain the X-shaped morphology observed in X-shaped radio galaxies. We test these scenarios by studying the BH mass, radio and optical luminosity, starburst history and dynamic age of radio lobes in a sample of X-shaped radio galaxies and in a control sample of radio-loud active nuclei with similar redshifts and optical and radio luminosities. We find that the X-shaped sources have statistically higher BH mass and older starburst activity than the objects from the control sample. Implications of these findings are discussed for the BH merger scenario and for the potential presence of active secondary BHs in post-merger galaxies.

1 Introduction

X-shaped (or "winged") radio galaxies are a class of extragalactic radio sources with two low-surface-brightness radio lobes (the "wings") oriented at an angle to the active, or high-surface-brightness, lobes [12]. Both sets of lobes often pass symmetrically through the center of the host galaxy, giving the galaxy an X-shaped morphology in the radio maps. Several scenarios were proposed for the formation of such peculiar radio morphology (backflow from the active lobes into the wings [12]; reorientation of the jet axis [5]; reorientation of a black hole (BH) spin axis due to a minor merger which may lead to a sudden flip in the direction of the associated jet [14]). Other authors suggested that at least some of the X-shaped sources may contain coalescing binary supermassive black hole (SMBH) systems with two pairs of jets associated with two unresolved AGN (e.g., [10]).

In all schemes in which X-shaped objects are the product of galactic mergers, the properties of the nuclear region will be affected by the past SMBH merger or the presence of a secondary SMBH. This should then be reflected by statistically higher masses of the central BHs in the X-shaped galaxies. If the X-shaped morphology is indeed caused by a profound event in the nuclear region, such as a merger of two SMBH, then it may also be reflected in the starburst history of the host galaxy. Investigations of the BH masses and starburst histories of the X-shaped sources can therefore address the question of their physical nature.

2 The sample

The sample of AGN analysed in this paper is drawn from a list of known X-shaped sources and a list of 100 "winged" and X-shaped radio source candidates [3].

Our final sample comprises 29 X-shaped radio sources with Sloan Digital Sky Survey (SDSS DR6 [1]) spectra, all showing well-detected stellar absorption lines.

We also compile a control sample of 36 radio-loud sources [13, 6, 9] that have SDSS spectra, and cover the same ranges of redshift ($z < 0.3$), optical and radio luminosities as the objects in the target sample. The resulting common luminosity ranges for both samples are: log $\lambda L_{5100\text{Å}} \in [43.0, 46.0]$ and log $\nu L_{1.4\text{GHz}} \in [39.0, 44.5]$. According to the Kolmogorov-Smirnov test (KS-test) the two samples differ at $0.9\,\sigma$, which warrants making statistical comparisons between them.

3 Data analysis

We use the stellar population synthesis code STARLIGHT [4] to model the observed spectrum O_λ of both samples. The best fit is obtained using a linear combination of simple stellar populations (SSPs [2]) and power-laws for the AGN continuum emission.

The STARLIGHT model for the observed spectra yields the stellar velocity dispersion σ_*, from which we derive the BH mass using the empirical $M_{\rm BH} - \sigma_*$ relation [8, 19], and the light fraction x_j, mass fraction $M_{{\rm ini},j}$, age τ_j, and metallicity Z_j of the stellar populations used in the fit. We use these parameters to derive starburst histories and apply Gaussian smoothing to the individual starburst events in order to determine the epoch of the most recent starburst episode.

3.1 Optical continuum

We estimate the rest-frame continuum flux at 5100 Å from the SDSS photometry [20]. To assess the spectral classification of the X-shaped and control host galaxies, we measure the Ca II break ($C_{\rm CaII}$) of their absorption optical spectrum [11]. This break is typically seen in the spectrum of elliptical galaxies and it has been used as an additional criterion to separate blazars from radio galaxies [16].

3.2 Dynamic age of radio lobes

The dynamic age of the high-surface-brightness (active) radio lobes is given by $\theta_\mathrm{a}/v_\mathrm{a}$, where θ_a is the angular size in the FIRST image and v_a is the lobe advance speed (we adopt $v_\mathrm{a} \approx 0.1\,c$, cf. [18]).

Assuming that the fuelling of the low-surface-brightness lobes of the X-shaped sources had stopped after the high-surface ones were activated, the dynamic age of the passive lobes t_p during their active stage can be estimated as

$$t_\mathrm{p} = \frac{\theta_\mathrm{p} - t_\mathrm{a} v_\mathrm{p}}{v_\mathrm{a}}\,, \quad (1)$$

where θ_p is the angular size of the low-surface brightness lobes and v_p is their expansion speed during the inactive stage. We use $v_\mathrm{p} = 0.01\,c$ in our calculation.

4 Results

Combined results from fitting the optical spectra, BH mass calculations, and age measurements for the radio lobes and most recent starbursts are presented in Tables 1–2 in [15][1].

4.1 Luminosity matching

Luminosity matching between the target and control samples is illustrated in Fig. 1 (left), where the continuum luminosities derived from the SDSS magnitudes are plotted against the radio luminosities at 1.4 GHz. The entire radio-optical luminosity range including all the sources is designated as Region 0. To provide a tighter match between the samples, we define a smaller subregion (shown in Fig. 1, left) called Region 1 that ranges from log $\lambda L_{5100\mathrm{\AA}} \in [43.5,\ 44.25]$ to log $\nu L_{1.4\mathrm{GHz}} \in [40.25,\ 42.5]$. The KS-test indicates that the statistical difference between the two samples in Region 1 is $0.9\,\sigma$ for the optical luminosity and $1.0\,\sigma$ for the radio luminosity.

4.2 Spectral classification

All the X-shaped sources analysed have $C_\mathrm{CaII} > 0.25$, with 92 % of the sources (23 out of 25) having $C_\mathrm{CaII} \simeq 0.4$. These values ensure that the host galaxy of the X-shaped objects is elliptical and that it is dominated by the thermal spectrum. For the control sample, however, the Ca II break can be determined for only 20 out of the 36 sources. Therefore only 56 % of the control sources have a thermal spectrum dominating the host elliptical galaxy.

We use the g, r and u magnitudes obtained from SDSS to plot a $g{-}r$ vs. $u{-}g$ color-color diagram (Fig. 1, right). We include in this plot only the sources with spectrum dominated by the host galaxy (as determined from the Ca II break). According to the distribution of galaxies in the $g - r$ vs. $u - g$ diagram from [17], all galaxies lying above the $u - r = 2.22$

[1] For the sake of brevity, we do not include these tables here.

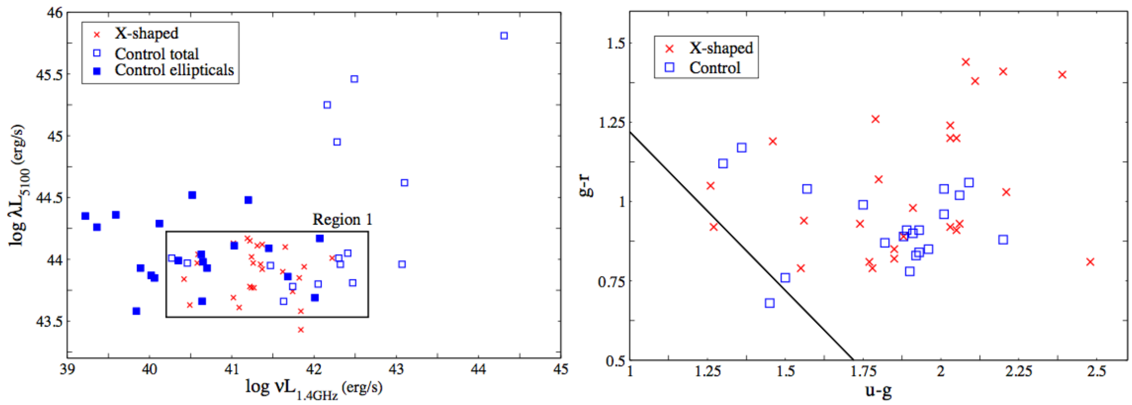

Figure 1: *Left:* Optical continuum luminosity versus radio luminosity at 1.4 GHz for X-shaped (crosses) and control sources (squares). *Right:* Color-color diagram for X-shaped sources (cross) and control sample (square). Black line: $u - r = 2.22$ galaxy type separator from [17].

separator line are elliptical systems. This is the case for all the X-shaped radio sources and for all the control sources for which the SDSS magnitudes are available, with only one source from each of the samples lying slightly under the $u - r = 2.22$ separator line. This spectral classification is in agreement with the results obtained using the Ca II break feature and confirms that all the X-shaped analysed are hosted by elliptical galaxies.

In order to study better the relation between the galactic hosts of the X-shaped and control radio sources, we will also consider a control subsample of elliptical galaxies containing the 20 control sources for which the $C_{\rm CaII}$ value could be determined.

4.3 Black hole masses

Comparison of the BH masses derived for objects in Region 1 yields ratios of mean BH mass ranging between $1.94^{+0.42}_{-0.34}$ for X-shaped/control (all) to $1.50^{+0.36}_{-0.29}$ for X-shaped/control (ellipticals).

60% of the X-shaped sources have $\log M_{\rm BH} > 8.25 \times 10^7$ M$_\odot$, while only 25 % of the whole control sample does. The X-shaped objects show, thus, a tendency to having higher BH masses. The KS-test indicates that the mass distributions of the two samples are different at a statistical significance of $1.9\,\sigma$.

The statistically higher BH mass of the X-shaped sample implies that these objects are possibly located in galaxies that have undergone strong major activity in the past, with either one major merger event or multiple minor mergers.

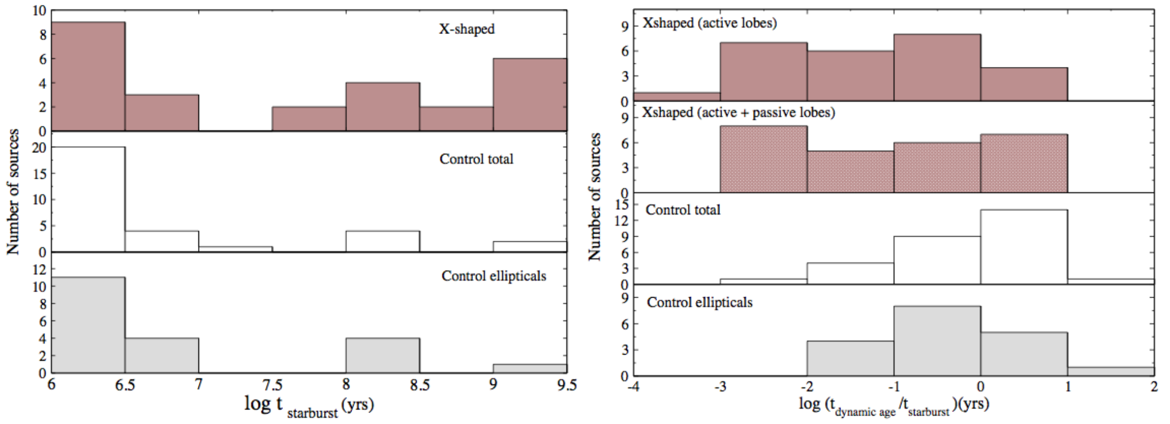

Figure 2: *Left:* Histogram of the recent starburst for X-shaped sources (top), control all (middle), and control ellipticals (bottom) in Region 0. *Right:* Logarithmic ratios of the dynamic age of the radio emission to the age of the most recent starburst for Region 0 (see text).

4.4 Starbursts

A sizeable fraction of objects in both samples (Fig. 2, left) have relatively recent starbursts, with ages of $10^{6.0}$–$10^{6.5}$ years, possibly related to the current jet activity. The starburst age distribution of the X-shaped sample is much broader, with half of the objects having starbursts older than 10^8 years, while only 19 % of all the control sources and 25 % of the control ellipticals exhibit such starbursts. Since the largest dynamic age of the active lobes is $\sim 10^7$ years (see Tables 1 and 2, col. 8 in [15]), any starburst activity significantly older than 10^7 years is not likely to be related to the active lobes. It can be speculated that these older starbursts are related to galactic mergers themselves or to the putative coalescence of the central BHs in post-merger galaxies.

The KS-test applied to the distributions of the most recent starburst ages gives a statistical significance of 2.3 σ for the two samples being different.

The mean logarithmic ratios of the dynamic age and most recent starburst age are -1.29 ± 0.23 and -0.14 ± 0.18 for the X-shaped objects and the control sample, respectively. The X-shaped sources tend to have starburst ages larger than the dynamic ages of the radio lobes (Fig. 2, right), while in both the control sample and the subsample of ellipticals these ages are comparable. The KS-test shows that the ratio distributions are different at a statistical significance of 2.8 σ. The starburst activity in X-shaped sources is therefore likely not related to the active lobes.

This difference in the starburst/dynamic age ratios may support the scenario in which the active lobes of the X-shaped sources are due to a possible reorientation caused by a BH merger [14] that leaves the old low-surface-brightness lobes inactive. Assuming that the low-surface-brightness lobes became inactive when the high-surface ones were activated, the dynamic age of the passive lobes during their active stage can be determined using Eq. 1.

The ratio of the total dynamic age of the active plus passive lobes to the starburst age is plotted in Fig. 2 (right; second panel), and it indicates that the starburst age still remains older than the total dynamic age of the lobes. This suggests that the starburst activity in X-shaped sources had occured before the possible reorientation due to a BH merger, and it may have been related to the galactic merger itself.

5 Summary

We have provided detailed insight on the most likely scenario for the formation of the X-shaped morphology in X-shaped radio galaxies.

We find that: 1) all the X-shaped radio sources studied are hosted by elliptical galaxies, which suggests that the X-shaped morphology could be related to the galaxy merger scenario according to the hierarchical galaxy formation model [7]; 2) the mean BH mass of the X-shaped sample is statistically higher than in the control sample; 3) the most recent starburst activity in X-shaped sources is older than in the control sample; and 4) X-shaped radio sources had their most recent starburst before their active lobes were formed. These results lend further support to the presence of two active central engines in the nuclear region of X-shaped radio galaxies or to the scenario in which the high-surface-brightness lobes of the X-shaped sources might have become active due to reorientation caused by a BH coalescence.

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