

Black Hole Masses in X-shaped radio sources

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Introduction

X-shaped radio galaxies are a class of extragalactic radio sources with two low-surfacebrightness radio lobes (the "wings") oriented at an angle to the active, or high-surfacebrightness, lobes. Both sets of lobes pass symmetrically through the center of the elliptical galaxy that is the source of the lobes, giving the galaxy an X-shaped morphology as seen on radio maps.

It has been suggested that the X-shaped morphology can reflect either a recent merger of two Supermassive Black Holes (SMBHs) or the presence of a second active black hole in the galactic nucleus.

This scenario is studied by determining the mass and luminosity of a sample of 22 X-shaped radio galaxies drawn from a list of 100 X-shaped radio source candidates presented by Cheung 2007 using the FIRST (Faint Images of the Radio Sky at Twenty cm) survey. The results are compared to the ones obtained for a sample of 25 radio-loud active nuclei from Marchesini et al. 2004 with similar redshifts (z < 0.3) and luminosities whose spectra are found in the SDSS (Sloan Digital Sky Survey).



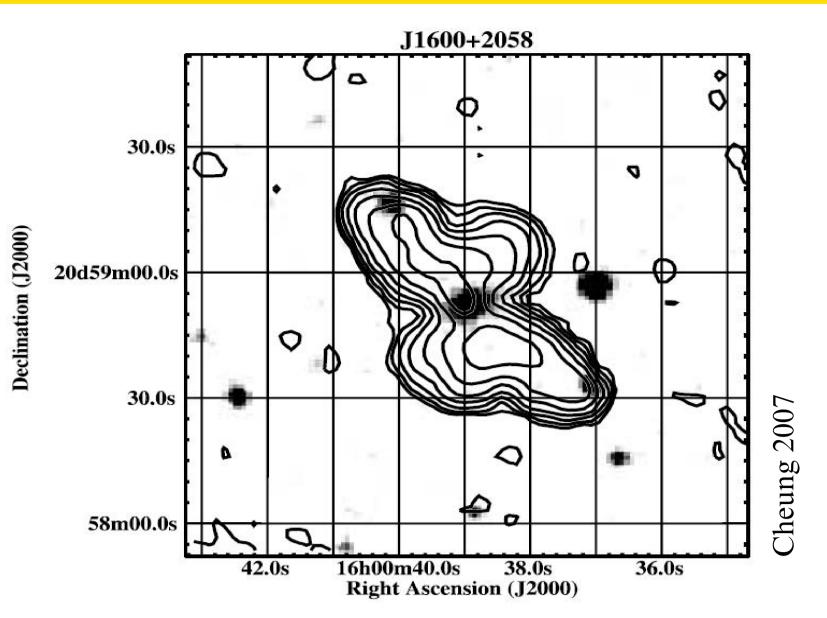


Fig. 1. Images of one of the 100 FIRST X-shaped radio source candidates (J1600+2058). Left, color image from VLA FIRST 1.4GHz. Right, FIRST contours overlaid on the optical image.

Analysis	The modeled spectrum is then subtracted from the observed one as shown in Fig. 2 and the residual spectrum	Table 1					
Our analysis is based on two approaches:	obtained is used to measure the emission-line parameters.	X-shaped					
1. Comparing black hole masses in the X-shaped		Name	σ_*	$\log M_{BH} \sigma_*$	$\log \lambda L_{5100 { m \AA}} \sigma_*$	$\log \lambda L_{5100 { m \AA}}$ SDSS	$\log \lambda L_{1.4GHz}$
sources and in a sample of radio-loud AGNs with similar radio and optical luminosities and similar	Assuming that the kinematics of the stars in the bulge of the host galaxies of AGNs reflects the gravitational		(km/s)	(M_{\odot})	(erg/s)	(erg/s)	(erg/s)
optical colors.	influence of the central SMBH, the black hole mass $M_{_{\rm BH}}$	(1)	(2)	(3)	(4)	(5)	(6)
2. Comparing black hole masses obtained from stellar	can be derived using the relation from Tremaine et al.	J1424+2637	174.99 ± 6.53	7.90 ± 0.07	40.48 ± 6.37	43.97	39.03
velocity dispersion (σ_*) with the ones obtained from	2002: σ	J1207+3352	181.28 ± 3.79		41.85 ± 0.84	44.13	38.32
the FWHM of the broad emission lines assuming that	$M_{BH} = 1.349 \ x \ 10^8 \ M_{\odot} \ (\frac{\sigma_*}{200 \ km \ s^{-1}})^{4.02 \pm 0.32}$	J1043+3131	195.27 ± 8.24		41.15 ± 1.15	43.63	38.86
the gas in the Broad Line Region is virialized (Kaspi et	Since most of the X-shaped radio galaxies and some of	J1140+1057	196.37 ± 7.80		40.51 ± 20.11	43.61	38.44
al. 2000). Since a non-active nucleus would contribute to the mass determined from (σ_*) while the virial mass	the comparison sample sources are obscured AGNs, their	J1040+5056			2 <u>11</u> 3	43.77	37.11
	continuum flux cannot be provided by STARLIGHT but		219.35 ± 7.72		-	44.04	36.83
is due only to an active nucleus, this comparison would help us to determine whether X-shaped radio	using the formula from Wu & Liu 2004:	J1210+1121			-	43.96	36.66
galaxies are formed by an active and a non-active	$f_{5100\text{\AA}}(Jy) = 3631 \ x \ 10^{-0.4g} \ [\frac{4700}{5100(1+z)}]^{-(g-r)/2.5\log(6231/4770)}$	J1455+3237 J0924+4233	224.17 ± 5.52 231.16 ± 15.72		41.57 ± 1.78	43.84	36.34
nucleus both remains of the coalescence of two	where z is the redshift and g and r magnitudes are	J1444+4147	231.10 ± 13.72 226.06 ± 9.35		3 7 43	43.58	37.69
SMBHs.	obtained from SDSS.	J1327-0203	220.00 ± 9.33 237.30 ± 9.27		ti n us ange	43.74	37.99 39.49
The 22 X-shaped radio sources analyzed are the only	3	J0838+3253			21 4 73	44.01 43.92	36.52
ones from the 100 candidates list from Cheung 2007	2.5	J0858+5255	241.00 ± 11.43 251.25 ± 5.79			43.92	37.82
that are spectroscopically identified in the latest SDSS	2 -	J1111+4050			_	44.17	38.99
data release (DR6). We used the stellar population synthesis code	2	J1005+1154				44.12	37.22
STARLIGHT (Cid Fernandes et al. 2004) to model		J0049+0059				43.43	36.86
the observed spectra of the X-shaped and comparison		J0001-0033	277.32 ± 4.55		8 	43.77	35.84
sample sources. STARLIGHT models each spectrum	0.5	J1339-0016	323.77 ± 4.55			44.15	37.20
by a linear combination of synthetic stellar populations and provides the stellar velocity	O Land and the second s	J1625+2705	204.27 ±4.54	8.12 ± 0.04	2 <u>43</u> 3	45.13	38.51
dispersion and the powerlaw continuum flux at 5100Å	4000 5000 6000 7000 8000 9000 Wavelength (Angstroms)	J1015+5944	248.16 ± 3.90	8.75 ± 0.02	8 <u>1</u> 73	45.18	37.42
of the host galaxy.	Fig. 2. Spectrum of the X-shaped source J1424+2637.						
of the nost galaxy.	Fig. 2 . Speetrum of the X-shaped source J 1424 + 2057.	Table 2					
		Table 2 Marchesini s	ample				
Results The measure of the width of broad emission lines needed	44.4 - Xshaped -	A Management and and and		$\log M_{BH} \sigma_*$	$\log \lambda L_{5100\text{\AA}} \sigma_*$	$\log \lambda L_{51004}$ SDSS	$\log \lambda L_{1.4GHz}$
Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three	44.4 44.4 X- 44.2	Marchesini s	ample σ_* (km/s)	$\log M_{BH} \sigma_*$ (M_{\odot})	$\log \lambda L_{5100 \text{\AA}} \sigma_*$ (erg/s)	log λL _{5100Å} SDSS (erg/s)	$\log \lambda L_{1.4GHz}$ (erg/s)
Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three shaped sources and eleven sources from the compary	44.4 44.4 X- Son 44.2 44.2 44.2 44.2 44.2 44.2 44.2 44.2 44.2 44.2 44.2 44.2 44.2 44.2 44.4 44.2 44.4 44.2 44.4 44.2 44.4 44.4 44.2 44.4 44.2 44.4 44.2 44.4 44.2 44.4 44.4 44.4 44.2 44.4 44.2 44.4 44.	Marchesini s	σ.				
Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three shaped sources and eleven sources from the compare sample and therefore it does not allow us to compare the	$\begin{array}{c} 44.4 \\ 44.4 \\ 44.2 \\ 44.2 \\ 50n \\ 68e \\ 6$	Marchesini s	σ _* (km/s) (2)		(erg/s)	(erg/s)	(erg/s)
Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three shaped sources and eleven sources from the compar- sample and therefore it does not allow us to compare the masses with the ones obtained from the velocity dispersion	A to X- 44.4 44.4 44.2 44.4	Marchesini s Name (1)	σ_{*} (km/s) (2) 144.35 ± 9.53	(<i>M</i> _☉) (3)	(erg/s) (4)	(erg/s) (5)	(erg/s) (6)
Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three shaped sources and eleven sources from the compar- sample and therefore it does not allow us to compare the masses with the ones obtained from the velocity dispersion To compare the X-shaped radio galaxies sample with	I to 44.4 A Xshaped Comparison sample Comparison sample A A A A A A A A A A A A A A A A A A A	Marchesini s Name (1) 3C197.1	σ_{*} (km/s) (2) 144.35 ± 9.53	(M_{\odot}) (3) 7.56 ± 0.12	(erg/s) (4)	(erg/s) (5) 43.80	(erg/s) (6) 38.07
Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three shaped sources and eleven sources from the compar- sample and therefore it does not allow us to compare the masses with the ones obtained from the velocity dispersion To compare the X-shaped radio galaxies sample with Marchesini sample we plot the continuum luminosity from the second seco	A to X- 44.4 44.4 44.2 43.8 43.6	Marchesini s Name (1) 3C197.1 3C285	σ_* (km/s) (2) 144.35 ± 9.53 162.58 ± 9.46 164.35 ± 5.76	(M_{\odot}) (3) 7.56 ± 0.12 7.77 ± 0.10	(erg/s) (4) 43.46 ± 0.05 -	(erg/s) (5) 43.80 43.86	(erg/s) (6) 38.07 37.70
Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three shaped sources and eleven sources from the compare sample and therefore it does not allow us to compare the masses with the ones obtained from the velocity dispersion. To compare the X-shaped radio galaxies sample with Marchesini sample we plot the continuum luminosity for SDSS magnitudes vs. the radio luminosity at 1.4 GHz	A to X- 44.4- 44.4- 44.4- 44.4- 44.2- 43.8- 43.6- 43.6- 43.6- 43.4-	Marchesini s Name (1) 3C197.1 3C285 3C198	σ_* (km/s) (2) 144.35 ± 9.53 162.58 ± 9.46 164.35 ± 5.76	(M_{\odot}) (3) 7.56 ± 0.12 7.77 ± 0.10 7.79 ± 0.06	(erg/s) (4) 43.46 ± 0.05 - 43.46 ± 0.02	(erg/s) (5) 43.80 43.86 43.66	(erg/s) (6) 38.07 37.70 37.65 38.49 38.34
Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three shaped sources and eleven sources from the comparison sample and therefore it does not allow us to compare the masses with the ones obtained from the velocity dispersion. To compare the X-shaped radio galaxies sample with Marchesini sample we plot the continuum luminosity for SDSS magnitudes vs. the radio luminosity at 1.4 GHz determine a common range of log $\lambda L_{5100\text{\AA}} \in [43.61, 44]$	A to X_{-} x_{-	Marchesini s Name (1) 3C197.1 3C285 3C198 3C223 3C223 3C303 3C219	σ_* (km/s) (2) 144.35 ± 9.53 162.58 ± 9.46 164.35 ± 5.76 181.42 ± 8.26 167.41 ± 9.77 188.98 ± 8.49	(M_{\odot}) (3) 7.56 ± 0.12 7.77 ± 0.10 7.79 ± 0.06 7.96 ± 0.08 7.82 ± 0.10 8.03 ± 0.08	(erg/s) (4) 43.46 ± 0.05 - 43.46 ± 0.02 43.45 ± 0.06	(erg/s) (5) 43.80 43.86 43.66 43.81 43.96 43.96	(erg/s) (6) 38.07 37.70 37.65 38.49 38.34 39.09
Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three shaped sources and eleven sources from the comparts sample and therefore it does not allow us to compare the masses with the ones obtained from the velocity dispersion. To compare the X-shaped radio galaxies sample with Marchesini sample we plot the continuum luminosity for SDSS magnitudes vs. the radio luminosity at 1.4 GHz determine a common range of log $\lambda L_{_{5100A}} \in [43.61, 44]$ and log $\lambda L_{_{1.4GHz}} \in [36.29, 39.09]$ (Fig. 3). In this common range of log $\lambda L_{_{1.4GHz}} \in [36.29, 39.09]$ (Fig. 3).	A to X - 44.4 A	Marchesini s Name (1) 3C197.1 3C285 3C198 3C223 3C303 3C219 3C219 3C192	σ_* (km/s) (2) 144.35 ± 9.53 162.58 ± 9.46 164.35 ± 5.76 181.42 ± 8.26 167.41 ± 9.77 188.98 ± 8.49 209.94 ± 7.97	(M_{\odot}) (3) 7.56 ± 0.12 7.77 ± 0.10 7.79 ± 0.06 7.96 ± 0.08 7.82 ± 0.10 8.03 ± 0.08 8.21 ± 0.07	(erg/s) (4) 43.46 ± 0.05 - 43.46 ± 0.02 43.45 ± 0.06 44.22 ± 0.01 43.52 ± 0.07 -	(erg/s) (5) 43.80 43.86 43.66 43.81 43.96 43.96 43.85	(erg/s) (6) 38.07 37.70 37.65 38.49 38.34 39.09 37.84
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Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three shaped sources and eleven sources from the comparts sample and therefore it does not allow us to compare the masses with the ones obtained from the velocity dispersion. To compare the X-shaped radio galaxies sample with Marchesini sample we plot the continuum luminosity for SDSS magnitudes vs. the radio luminosity at 1.4 GHz determine a common range of log $\lambda L_{_{5100\text{\AA}}} \in [43.61, 44]$ and log $\lambda L_{_{1.4\text{GHz}}} \in [36.29, 39.09]$ (Fig. 3). In this commange, the mean $M_{_{BH}}$ is (Fig. 4): • X-shaped sample:	A to X- son tese n. the om and 1.7] hon 44.4 43.6 36 37 $1_{12}(\text{erg/s})$ 5 5 5 5 5 5 5 5	Marchesini s Name (1) 3C197.1 3C285 3C198 3C223 3C223 3C303 3C219 3C219 3C192 1613+27 3C227	σ_* (km/s) (2) 144.35 ± 9.53 162.58 ± 9.46 164.35 ± 5.76 181.42 ± 8.26 167.41 ± 9.77 188.98 ± 8.49 209.94 ± 7.97 221.13 ± 6.13 152.62 ^a ± 0.39	(M_{\odot}) (3) 7.56 ± 0.12 7.77 ± 0.10 7.79 ± 0.06 7.96 ± 0.08 7.82 ± 0.10 8.03 ± 0.08 8.21 ± 0.07 8.31 ± 0.05 7.66 ± 0.00	(erg/s) (4) 43.46 ± 0.05 - 43.46 ± 0.02 43.45 ± 0.06 44.22 ± 0.01 43.52 ± 0.07 - 42.11 ± 0.40 44.63 ± 0.00	(erg/s) (5) 43.80 43.86 43.66 43.81 43.96 43.96 43.95 43.99 43.95	(erg/s) (6) 38.07 37.70 37.65 38.49 38.34 39.09 37.84 36.37 37.49
Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three shaped sources and eleven sources from the comparison sample and therefore it does not allow us to compare the masses with the ones obtained from the velocity dispersion. To compare the X-shaped radio galaxies sample with Marchesini sample we plot the continuum luminosity for SDSS magnitudes vs. the radio luminosity at 1.4 GHz determine a common range of log $\lambda L_{5100\text{\AA}} \in [43.61, 44]$ and log $\lambda L_{1.4\text{GHz}} \in [36.29, 39.09]$ (Fig. 3). In this commange, the mean M_{BH} is (Fig. 4): • X-shaped sample: $M_{BH} = 23.28^{+3.7}_{-3.2} \times 10^7 M_{\odot}$	I to X- son lese n. $(y_{0})^{(y_{0})}$, $(y_{0})^{(y_{0})}$, $(y_$	Marchesini s Name (1) 3C197.1 3C285 3C198 3C223 3C223 3C303 3C219 3C219 3C219 3C192 1613+27 3C227 3C227 0755+37	σ_* (km/s) (2) 144.35 ± 9.53 162.58 ± 9.46 164.35 ± 5.76 181.42 ± 8.26 167.41 ± 9.77 188.98 ± 8.49 209.94 ± 7.97 221.13 ± 6.13 152.62 ^a ± 0.39 251.55 ± 4.63	(M_{\odot}) (3) 7.56 ± 0.12 7.77 ± 0.10 7.79 ± 0.06 7.96 ± 0.08 7.82 ± 0.10 8.03 ± 0.08 8.21 ± 0.07 8.31 ± 0.05 7.66 ± 0.00 8.53 ± 0.03	(erg/s) (4) 43.46 ± 0.05 - 43.46 ± 0.02 43.45 ± 0.06 44.22 ± 0.01 43.52 ± 0.07 - 42.11 ± 0.40 44.63 ± 0.00 42.58 ± 0.09	(erg/s) (5) 43.80 43.86 43.66 43.81 43.96 43.96 43.96 43.95 43.99 43.95 44.48	(erg/s) (6) 38.07 37.70 37.65 38.49 38.34 39.09 37.84 36.37 37.49 37.22
Results The measure of the width of broad emission lines needed determine the virial mass was possible in only three shaped sources and eleven sources from the comparts ample and therefore it does not allow us to compare the masses with the ones obtained from the velocity dispersion. To compare the X-shaped radio galaxies sample with Marchesini sample we plot the continuum luminosity for SDSS magnitudes vs. the radio luminosity at 1.4 GHz determine a common range of log $\lambda L_{s100A} \in [43.61, 44]$ and log $\lambda L_{1.4GHz} \in [36.29, 39.09]$ (Fig. 3). In this commange, the mean M_{BH} is (Fig. 4): • X-shaped sample: $M_{BH} = 23.28^{+3.7}_{-3.2} \times 10^7 M_{\odot}$ • Comparison sample:	A to X- son tese n. the om and 17] non Fig. 3. Continuum luminosity from SDSS vs. radio luminosity. The orange square shows the common range. 95 $10^{44,4}$ 44,4 44,4 44,4 44,4 44,4 44,4 44,4 44,4 44,4 44,4 44,4 44,4 44,4 43,4	Marchesini s Name (1) 3C197.1 3C285 3C198 3C223 3C223 3C23 3C219 3C219 3C192 1613+27 3C227 0755+37 3C236	σ_* (km/s) (2) 144.35 ± 9.53 162.58 ± 9.46 164.35 ± 5.76 181.42 ± 8.26 167.41 ± 9.77 188.98 ± 8.49 209.94 ± 7.97 221.13 ± 6.13 152.62 ^a ± 0.39 251.55 ± 4.63 247.41 ± 7.26	(M_{\odot}) (3) 7.56 ± 0.12 7.77 ± 0.10 7.79 ± 0.06 7.96 ± 0.08 7.82 ± 0.10 8.03 ± 0.08 8.21 ± 0.07 8.31 ± 0.05 7.66 ± 0.00 8.53 ± 0.03 8.50 ± 0.05	(erg/s) (4) 43.46 ± 0.05 - 43.46 ± 0.02 43.45 ± 0.06 44.22 ± 0.01 43.52 ± 0.07 - 42.11 ± 0.40 44.63 ± 0.00	(erg/s) (5) 43.80 43.86 43.86 43.86 43.96 43.96 43.96 43.95 43.99 43.95 44.48 44.17	(erg/s) (6) 38.07 37.70 37.65 38.49 38.34 39.09 37.84 36.37 37.49 37.49 37.22 38.09
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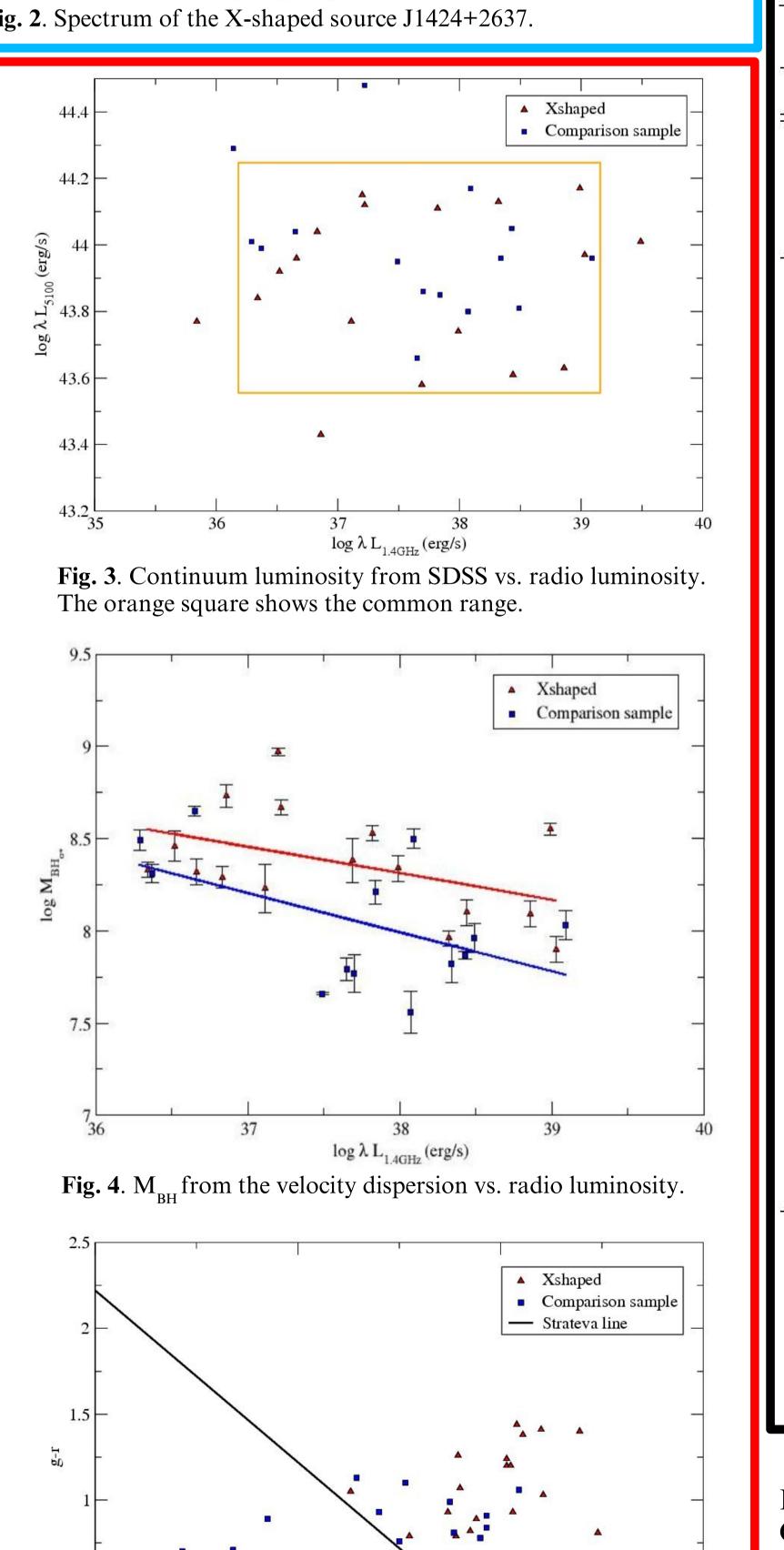


Fig. 5. g-r vs. u-g magnitudes. Black line, u-r =2.22 separator.

0.5

Conclusions

Under the merger hypothesis, elliptical galaxies are the product of mergers. Since all the X-shaped sources studied here are shown to be elliptical and are different to the comparison sample at an statistical significance of 1.35σ , the $M_{_{\rm PL}}$ of the X-shaped sample being twice the one of the control sample suggests the possible presence of two central engines in

the center of X-shaped radio sources and strengthens the scenario of X-shaped radio sources containing two SMBHs or resulting from a recent coalescence of two SMBHs.

Col.(1) Names used in Cheung 2007 and Marchesini et al. 2004 papers. Col.(2) Stellar velocity dispersion obtained from STARLIGHT. Col.(3) BH mass obtained from the relation of Tremaine et al. 2002. Col.(4) Continuum luminosities at 5100Å obtained from the velocity dispersion. Col.(5).Continuum luminosity obtained from SDSS magnitudes. Col.(6) Radio luminosity fluxes in 1.4 GHz.

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