Radio Galaxies
Abstract

It is thought that all galaxies have a massive black hole at their centre which must have been made during the formation of the galaxy itself. During this stage the galaxy may appear as a Radio Galaxy, with extremely powerful jets emerging from near the black hole and drilling out of the radio galaxy, producing spectacular structures. This project collected a large sample of radio galaxies and used the available data to investigate the different properties and evolution of radio galaxies. The results from this project show the expected radio luminosity difference in relation to the Fanaroff-Riley type I/Fanaroff-Riley type II dichotomy. Galactic mergers are presumed to play a large part in radio galaxy evolution and different scenarios are put forward and tested against the gathered data. It was calculated that X-shaped galaxies in this project showed double the average for the black hole mass than other galaxies in a comparable control sample. This is used to support and discuss the idea of binary black holes and galaxy mergers. The double-core of Double-double radio galaxies was investigated and related to known examples of merging galaxies, such as 3C 75 and CGCG 292 –057.
Introduction

As it is now believed that massive black holes (BH) exist at the centres of all large galaxies, then the BH must form during the formation of the galaxy itself. During this stage the galaxy may appear as a Radio Galaxy (RG) or quasi-stellar radio source (QSO), with extremely powerful jets emerging from near the BH and drilling out of the RG, producing spectacular structures\(^1\). This suggests that gas accretion onto the growing BH is related to these jets\(^2\). The radio emission is synchrotron: produced by relativistic electrons accelerated within a magnetic field\(^3\).

In this project, RGs will be explored through data available from virtual observatories and the journal literature. The major objective will be to determine if the jets provide one-off feedback or continuous over a billion years. Evidence for repeated episodes will be sought. Are there relic radio sources?

This project included the collection of data on a range of radio galaxies. Sources used form the 3CRR catalogue and journal literature already have each galaxy's morphology determined. For other sources the morphology was determined by examining radio contour plots obtained from the NASA virtual observatory Skyview (http://skyview.gsfc.nasa.gov).

Extended double-lobe radio galaxies can be categorised by their morphology as a Fanaroff-Riley type I (FRI) source or a Fanaroff-Riley type II (FRII) source\(^4\). The difference in these morphologies is thought by some to arise from differences in the properties of the central BH. This project will compare and study a large number of FRI and FRII sources and their properties. The different mechanism for these two populations are still not fully understood and if they undergo different evolution it may be the case that their fundamental properties, such as the BH spin or jet composition, are also different.

X-shaped galaxies are a sub-class of FRII radio galaxies. X-shaped radio galaxies are a class of radio sources that have two low-surface-brightness radio lobes that are oriented at an angle to the active lobes. It is often observed that both sets of

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lobes pass regularly through the centre of its host galaxy. This is thought to give the galaxy an X-shaped morphology if looked at in radio frequency\(^5\).

It has been suggested that the morphology observed in X-shaped sources 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. Double-double radio galaxies (DDRGs) are a sub-class of FRII objects where the galaxies are found to have multiple pairs of lobes. It has been observed that all the lobes are strongly co-aligned to within a few degrees of each other. It has been suggested that x-shaped radio galaxies evolve into DDRGs\(^6\). DDRGs offer a unique opportunity to study large-scale radio sources with multiple episodes of jet activity.

This project will look at a number of X-shaped RG and DDRGs and their properties. If it is true that double-double radio galaxies evolve from X-shaped RG, then it is presumed that DDRG, just like the X-shaped morphology, should only be detected in FRII radio sources.

Note that the chance superposition of two radio galaxies on to the same field of view is likely to be very rare. However, a fascinating case of genuinely interacting radio galaxies is associated with the dumbbell galaxy NGC 1128 at the centre of an Abell cluster of galaxies at a redshift of \(z = 0.0231\). The radio object is 3C75, displaying unique intertwined jets and plumes emanating from a double nucleus. In this particular case, the interacting quadruple jets in 3C 75 bestow the title Mating Dance\(^7\). The radio jets are launched from the vicinity of two supermassive black holes separated by eight kilo parsecs. These black holes are in the dumbbell galaxy NGC 1128 at a redshift of \(z = 0.0231\). This example will be explored and related to the X-shaped and double-double sources.

To further study the relationship between a growing black hole and a growing galaxy, it is noted that many host galaxies of FRII radio galaxies at high redshift \(z > 0.6\) appear to harbour elongated optical galaxies\(^8\). Intriguingly, the major axis is often aligned with the radio axis. This 'alignment effect' is only a property of cosmologically distant radio galaxies.

\(^6\) Chen, Xian; Liu, Fukun “Relationship between X-shaped radio sources and double-double radio galaxies” Black Holes from Stars to Galaxies Proceedings of the International Astronomical Union, 2007, 238 pp. 341-342
\(^7\) Waldrop, M M., "Mating Dance of the Two Tailed Radio Source 3C75", Sci, 468, pp. 623
Some such galaxies are dissected into two colour components, an underlying red elliptical and a very blue elongated structure. Only the blue structure is aligned with the radio axis\(^9\). This strongly suggests that the radio jets are not forced to propagate along the major axis but, instead, generate the blue optical structure. In this scenario, the radio lobes heat and compress the gas-rich interstellar medium associated with these distant sources and so trigger large-scale star formation. Therefore, I will consider how these early universe radio galaxies (gigahertz peaked spectrum (GPS) and compact steep spectrum (CSS)) are related to the present day examples, with emphasis on the properties of the massive black hole.

**Background**

All galaxies are now thought to have a BH at the centre – but not all of them are active. Some galaxies known as active galactic nuclei (AGN) are thought to have an active BH which can be detected by us as high luminosities at non-visible wavelengths. It has been long suggested that AGN were powered by accretion onto SMBH \((10^6 \text{ and } 10^{10} \text{M}_\odot)\). It has only been more recently that the central engines of these AGN have been investigated and other theories put forward.

At the centre of an AGN, the accretion disk is formed from cold materials near to the BH. Dissipative processes occur in the disc which results in matter moved towards the central engine and angular momentum moved outwards. This also causes the accretion disc to heat up. A torus or ‘donut’ of material gathers around the disc and can become so hot and luminous that most of the host galaxies light may be hidden.

Jets are produced from some accretion discs. These twin jets are highly collimated and flow out near the disk, out of the host galaxies with high velocities in opposed directions. Exactly how the jets are produced is still not known. It is these different jets and the relative positions and orientation of them which is responsible for the different morphology of RGs.

Possible theories for the origins of radio sources

Galaxy mergers

Mergers between galaxies and the subsequent interaction that occur between the central engines could explain why power jets are able to form. Mergers could supply enough force to push enough gas into the region of a black hole in a way in that a disk galaxy on its own could not. This process is very efficient\(^{10}\) - meaning an enormous amount of angular momentum is removed from the gas which is then accreted on the BH fuelling the AGN. A merger between a halo and disk galaxy (with similar masses around \(5 \times 10^9\) M) has been observed\(^{11}\) and it was calculated that it took around \(7.5 \times 10^8\) years for gas to gather at 200 pc. Other research also confirms this and it is believed that the evolution of these gases is delicate\(^{12}\) and depending on whether the galaxy is bulge-dominated, or not, the gas acts in different ways.

If the galaxy does not have bulges then it is often seen that bars will develop during a merger. Gas flows inwards due to the merger forces and star forming regions are created\(^{13}\). Galaxies with bars see gas driven inwards towards the centre engine. The outcome from this process is that starbursts can occur relatively quickly and as a result a lot of gases are used up quickly which only leaves a small amount of gas to be pushed inwards during the final merger. Galaxies that have many bulges many not have any star forming regions\(^{14}\). Bulges may help to even out the effects of bar formation. This results in fewer stars forming which mean there is more gas to be pushed inwards during the final merger.

In this theory it is assumed that during the final merger there is enough gas pushed in to have an accretion disk round the BH, although this is a matter of contention.\(^{15}\)

Some argue that as the gas accumulates, grows in mass and becomes self-


gravitating then fragments may fall inwards towards to the BH$^{16}$. The origin of RGs could be explained by the gas being continuously accreted onto a fixed plane. The resulting transfer in angular momentum that then occurs increases the spin of the BH. This initial spin could power radio-loud AGN and could also be responsible for powering the jets$^{17}$. The amount of gas that is pushed into the centre by the merger can sometimes be larger than the mass of the black hole itself. If a large fraction of the mass is accreted into the BH then its spin would increase. Another suggestion is that the spin energy of a BH, which is already rotating rapidly, could be used by the newly formed accretion disk$^{18}$.

A RG may also form if a BH has spin prior to merger. In this case, and at large radii, it has been found that there is no relation between the spin axis and the plane of the accreted gas.$^{19}$ For galaxies with smaller radii it is thought that the Lense-Thirring precession effect (gravitomagnetic frame-dragging effect) and viscous damping are the probable reasons why the disk falls in to BH’s equatorial plane$^{20}$. This process makes the disk warped and there is evidence to suggest there is some link between this and the presence of radio sources.$^{21}$ For an accretion disk that conducts perfectly, it can be shown that the magnetic field is pulled in and concentrated around the core. It is these conditions under which powerful radio jets are normally produced$^{22}$. It would only take a very small amount of irregular resistivity to allow field to slip through the accreting material which could result in little or no build-up of field and a non RG. It is still not fully understood why the first process happens in elliptical and the second in disk galaxies.

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There are studies that find a correlation between merger/interaction events and AGN activity and also other studies find no such correlation.

**Binary black holes**

Galaxy mergers trigger all kinds of activity in the centre of the merger remnant. In particular, the presence of a binary black hole which has formed as a result of a recent major merger can trigger star forming. BBH in minor mergers could lead to the creation of hot spots.

In order for a large scale radio structure to be observable it is paramount that the jets orientation remains stable over large time scales (> $10^7$ yrs).

Observations from the VLBI have shown that the jets are replaced all the time and this occurs on very small time scales, just a matter of months. It is not very likely that jets get their power from by the orbital energy of the BH.

If the distance between the two BH in the binary is around a parsec then it is thought that the BH would be too far away to interact enough to generate enough power to provide continuous jet power. If the distance between the BH is smaller than a parsec, it would then be possible for a large enough interaction to happen. The distance between the BH would then decrease, due to gravitational radiation, finally ending in a merger of the BHs.

When BHs merge the spin of the new BH is thought of as the most significant effect. Let's consider two BH which both have a similar, but large, mass and zero spin. When these BH merge, the resulting BH gains a large amount of

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spin and has a high mass. It is BHs that spin rapidly and have a high mass like these that may produce powerful radio jets\textsuperscript{29}.

Instead if two BHs having a similar, but small, mass merge, then the resulting BH would have a small mass and be spinning rapidly. It is out of these minor mergers that a weak radio source with a low-luminosity nucleus would be found\textsuperscript{30}.

If two BHs have different masses (one with a large mass and one was a small one) and they coalesce, the outcome would be a BH with a large mass but with a low spin. This sort of merger has been used to explain weak radio source in a potentially bright AGN\textsuperscript{31}.

In BH mergers - where both the BH have a large and similar mass, and also have large spin - the result is a rapidly-spinning BH which has a large mass. It is thought that powerful radio sources are the result of these kinds of mergers. Major mergers should not happen often as the mass spectrum of BH should drop as the BH mass increases.\textsuperscript{32} Work has already been done which predicts that powerful RG which have been formed due to a major merger will cause the resulting BH to increase its spin.\textsuperscript{33} This is consistent with the data obtained through experiments that determine the luminosity function of FR II radio sources\textsuperscript{34}.

If two disk galaxies with roughly equal mass collide, it is postulated that the resulting galaxy would be an elliptical as the original galaxies disks could be absolutely obliterated during that one merger. If one galaxy is three times more massive than the other, then the disk from the most massive galaxy remains while the smaller galaxy would resemble a Seyfert, S\textsubscript{0}, galaxy.

If nuclear BH masses are correlated to the galaxy mass, then the fact that merging galaxies have to have similar mass to result in an elliptical, suggests

\textsuperscript{29} Chiabergw, W., Marconi, A. “On the origin of radio loudness in active galactic nuclei and its relationship with the properties of the central supermassive black hole”, ApJ, 416, 2011, pp. 917-926


that it would also be the case that the masses of the BH were statistically comparable\textsuperscript{35}. The starting conditions needed for a galaxy to become elliptical are of a similar nature to those needed for the BH to be formed spinning rapidly. This could not only be used to explain how powerful RG and elliptical galaxies are connected but also could help to explain the lack of non-radio galaxies. This would assume that the BH in elliptical galaxies are generally formed rotating rapidly\textsuperscript{36}.

If BHs mainly gather their spin through coalescing with other BH, then why is it that the spin increase due to disk accretion is less important? S\textsubscript{0} galaxies produce weak jets. Powerful radio jets that could be thought of ‘large-scale’ (bigger than 10 kiloparsec) have not yet been found, though they can be often produced in S\textsubscript{0} galaxies. It is here that the ISM should not let the jet propagate out of the galaxy. The nuclear region sees gas pushed towards it, which is probably due to a disturbance from the spiral’s gas disk, and is accreted by the BH at rates of less than \(10^{-1}\) MO yr\textsuperscript{-1}. Even with this extra mass there is not enough mass for BH to be able to transfer enough spin.

Accretion events that follow allow the gas to move towards the BH and the resulting effect overall of the small accretions in other planes is the BH always has a small spin. It is worth noting that this would not be applicable in major merger events due to the vast volume of gas being pushed into the centre. A solution to this problem may be to investigate the connection between RG galaxies and the accretion of this gas.

\textsuperscript{35} F. K. Liu “X-shaped radio galaxies as observational evidence for the interaction of supermassive binary black holes and accretion disc at parsec scale”, \textit{MNRAS}, \textbf{347}, 2004, pp. 1357-1369

Compact sources (GPS and CSS)

Around 40% of all powerful radio sources are made up from either GPS or CSS and have radio spectra which are simple and convex. The GPS sources have peaks close to 1 GHz and morphologically speaking have a size of less than 1 kpc. The CSS sources have larger peaks off around 100 MHz and morphologically speaking a size of less than 20 kpc.

An explanation as to why GPS and CSS sources are compact is that since they are young, the jets have jet to expand into large-scale lobes that we see in other radio sources. As time passes it is thought this would occur and that possibly compact CSS/GPS sources eventually evolve into extended, edge brightened FRII. If these sources really are young, then studying this early stage of radio activity and feedback in CSS and GPS sources may lead us to improving our understanding of galaxy evolution.

FRI and FRII

FRIs have the edge-darkened morphology and have subsonic lobes, while FRIIs have the edge-brightened morphology and supersonic lobes – FRIIs also tend to have higher radio luminosities than FRIs. The difference in morphology is due to how energy is transported in the radio galaxy. FRI objects have bright jets in their core, while FRIIs have fainter jets but are brighter at the ends of their lobes. FRIIs are able to move energy efficiently to the far ends of their lobes, while the FRI jets are less efficient in the sense that they lose a large amount of their energy as they propagate through the galaxy. It is highly probably that FRIs have evolved from FRIIs as all young AGN have been classified as FRIIs. There are three suggested ways a RG will evolve from FRII to FRI.

- In a minor merger, it is thought that a FRII would evolve into a FRI. As there are small, similar, masses involved, as long as they are below a certain mass ratio then this evolution process will be over before the BBH and the accretion disk have a chance to interact. During the minor

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merger the orientation of the jets changes. These changes are what form the structure which looks like an ‘S’. The time it takes for this structure to form is inversely related to the accretion rate\textsuperscript{41}. Due to this it is more likely to see this shape in luminous FRI radio sources. The orientations of the jets in most of the FRI are random in respect to the host galaxies galactic plane\textsuperscript{42}. FRI should make up around a fifth of all RG as they a high BBH mass ratio.\textsuperscript{43}.

- The second suggestion is that during major merges the high masses involved allow the BBH and the accretion disk to interact. This allows the accretion disk to become radiatively inefficient before the outer disks have had a chance to realign. The jets in these FRIs orientate randomly. These types of FRI radio sources would create larger jets than the FRIs created due to minor mergers. Major mergers are very rare, which also mean these type of FRIs (larger and with random jet orientation) are also rare.\textsuperscript{44}.

- Another theory is that most RG evolve from FRII into FRI after the BBH plane is aligned with the outer accretion disk and the galactic plane.\textsuperscript{45} It has been said that FRIs maybe become X-shaped and DDRGs, before changing from FRII to FRI. Jets in some FRIs are aligned instead with the minor axis of host galaxy as they are perpendicular to the galactic planes. Once these galaxies change into a DDRG, the radio jets can start up again at rate proportional to the accretion rate\textsuperscript{46}. The new RG would be of FRII morphology and it is thought these jets would be less luminous than what normal FRIs would produce. This is down to the fact that formation jet can form undisturbed over a long time period before the RG has the chance to evolve to a FRI from a FRII. This would mean that the observed sizes of these radio lobes for these FRIs

\textsuperscript{41} Kaiser, Christian R.; Best, Philip N. "Luminosity function, sizes and FR dichotomy of radio-loud AGN", \textit{MNRAS}, 381, 2007, pp. 1548-1560
\textsuperscript{46} Liu F.K., Zhang Y.H., "Supermassive black hole masses of AGNs with elliptical hosts" \textit{A&A}, 381, page 742-751
are as large as that of FRI radio sources formed due to minor mergers which is considerably less than the average size of FRIIs\textsuperscript{47}.

**DDRG**

FRIIs are known for emitting a pair of collimated jets from their galactic centre. These jets then go on form two radio-loud lobes. It is at this point where the jets velocity decreases due to ram-pressure by the IGM\textsuperscript{48}.

DDRG are a sub-category of FRIIs. In DDRG multiple pairs of lobes are found. It has been seen that all the radio lobes are highly co-aligned\textsuperscript{49}. DDR quasars have only been more recently discovered. The first of its kind was 4C 02.27\textsuperscript{50}. As these properties are not unique to DDRG and are not just happening in giant radio sources it could be postulated that this is just a fleeting stage in galactic evolution and is just a normal part of all AGN life’s that only occur for a short time period.

The inner (and second) pair of lobes in the DDRG 4C02.27 were used as observational evidence to support the idea that there was episodic activity occurring in inside the original jets remaining shell. Discovery and observations from the only known to date triple-double radio galaxy (TDRG) are also used to support this theory. This TDRG shows three pairs of lobes which are closely aligned. This TDRG gives us the opportunity to investigate processes which occur over millions of years. Further study into TDRG and discovery of more TDRG will enable deeper research into large scale RG evolution\textsuperscript{51}. As there is only 1 known TDRG, triple radio sources dynamical evolution have had to be investigated\textsuperscript{52} further by computer models. The models results supported the idea that the other lobes were being created in original jets remaining shell.

It has also been seen that DDRG also have strong emission-line spectra. They also have what can be referred to as “cross-correlation” function when the DDRGs are


compared to that of randomly selected galaxies. This may be the case for FRII galaxies, but it is not true for FRI galaxies. RG with low luminosities have a 4-5 times greater cluster factor than the average galaxy. If this is the case then RG should be seen in clusters and groups.

**X-shaped galaxies**

As well as DDRGs another sub-class of FRIIs are X-shaped RG. X-shaped RG have a pair of radio lobes oriented at angle to the active lobe. The lobes have low-surface-brightness. Both pairs of lobes are often seen to pass through the centre of their host galaxy. It is this which gives these galaxies their distinct radio morphology.

The distinct morphology of these galaxies has inspired many research papers and there have been several suggestions as to how they could possibly arise. One suggestion is that the X-shaped morphology is a result of a recent merger of SMBHs. Others have suggested there could be a BBH in the centre of these structures. It has also been considered that if the angular momentum of the SMBH and the gas accreted onto it are not aligned then the precession of the jets could account for the x-shaped. The active lobes could be providing backflow out towards the wings which could explain x-shaped galaxies.

Minor mergers could cause a change in direction of the BH spin. This could result in a change in direction for the jets. If this had occurred then X-shaped RGs would be the hosts of recently merged BH and would have undergone a flip in their spin. Therefore one set of wings would be an older relic of the old radio jets, while the other lobes would be showing evidence of a BH merger.

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A number of X-shaped RG have wings that have the same or a less steep spectral index than the centre lobes. Synchrotron aging is meant to show a steeper spectral index in the wings\textsuperscript{63}. To explain this difference it was suggested that some of these galaxies could harbour SMBH which have pairs of jets each coming from one of two AGN which cannot be resolved\textsuperscript{64}.

After a merger the SMBH's behaviour is related to the mass ratio of the BHs and also the distance is between them.\textsuperscript{65} Both BHs have the most time to remain active when mergers occur between BH with similar masses. Mergers involving BH with different masses are thought to allow fast depletion of the accretion disk which is around the BH with the smaller mass.\textsuperscript{66}.

It is worth noting however that the BH with the heavier mass in merger of BH with relatively small masses may remain active for a much longer period than that compared with the time taken in mergers where the BH have higher masses\textsuperscript{67}.

**Relationship between DDRG and X-shaped galaxies**

When minor mergers occur between BH with different masses, the accretion disk and the binary orbital plane become coplanar $10^7$–$10^8$ years after the X-shaped structure in a FRII has formed. The BH with the smaller mass creates an opening in its disk which allows angular momentum to be exchanged\textsuperscript{68}.

The smaller BH moves inwards towards the centre of the system and merges into the other BH. This process puts a stop to the formation of jets as the inner accretion disk has been completely eliminated\textsuperscript{69}. Many DDRG have been observed and some


are thought to show evidence of merger of SMBBH\textsuperscript{70} as well as disrupted jet formation and a removed inner disk\textsuperscript{71}.

The inner structure has a relatively low luminosity and is aligned to the old outer lobes. The new inner lobes in DDRGs are thought to exist due to the interactions between the hot clouds and episodic jet activity with interruption times of around 1 Myr\textsuperscript{72}. If the interruption time becomes a great deal less than $10^6$ years, then no new lobes would be produced as the interaction between the jets and the IGM would not produce new lobes\textsuperscript{73}.

In the theories of SMBBH merger and disk removal\textsuperscript{74} both would suggest that almost all the SMBBH in FRIIs would eventually join into one accompanying MBH and also all the X-shaped RG would change into DDRG. This ties in with observed data that DDRG have only ever been detected as FRIIs. This could be down to the outer disk and the outer plane being co-planar. The DDRG restarting jets would be perpendicular to the major axis of host RG and aligned with the wings from the X-shaped predecessor\textsuperscript{75}.

The jets in the DDRG and the old wings are co-planar, because of this so far it has been impossible to actually confirm by observing radio contours or other means if both these structures are both there. Although this coexistence cannot be confirmed, synchronicity of DDRG lobes and the cavities in the IGM is thought to be possible\textsuperscript{76}.

J0116-473 is a FRII but also contains double radio with low luminosity lobes and straight, sharp edges\textsuperscript{77}. The edges are the result of cavity formation in the IGM from the randomly oriented past jets. These jets are supplied with plasma from the outer lobes via back-flow.

\textsuperscript{75}F. K. Liu "X-shaped radio galaxies as observational evidence for the interaction of supermassive binary black holes and accretion disc at parsec scale", \textit{MNRAS}, \textbf{347}, 2004, pp. 1357-1369
\textsuperscript{76}F. K. Liu "X-shaped radio galaxies as observational evidence for the interaction of supermassive binary black holes and accretion disc at parsec scale", \textit{MNRAS}, \textbf{347}, 2004, pp. 1357-1369
If as suggested X-shaped RG evolve into DDRG, then it can also be presumed both are only found in FRIIs. It has been forecast that the detection rate of DDRG in a selection of FRIIs should be no more than 10%. RG would become a giant when they become DDRG, this is due to the rate of accretion needed to restart the jets is less than that needed in the outer, relic, lobes. This is why the jets in DDRG have lower luminosities and may never reach the relic lobes. If this is the case then the giant RG may form mainly due to the interaction of SMBBH which results in an accretion rate increase.

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Theory

The project began by collecting data on a range of different types of RG. Data was collected from online catalogues and surveys, data available from virtual observatories and journal literature. In order to carry out a detailed investigation of different radio galaxies, it was essential that specific data was collected. For example, the red shift of the galaxies needed to be collected so that the co-moving distance could be calculated for each galaxy.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Symbol</th>
<th>How it was collected</th>
<th>What it was used for</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redshift</td>
<td>$z$</td>
<td>Collected from catalogues and journal literature</td>
<td>To calculate the co-moving distance and Radio Luminosity</td>
<td>FRI$^{82}$</td>
</tr>
<tr>
<td>Spectral index</td>
<td>$\alpha$</td>
<td>Collected from catalogues and journal literature. Some were computed using equation (1).</td>
<td>To calculate the flux density</td>
<td>FRII$^{84}$ $^{85}$ $^{86}$</td>
</tr>
<tr>
<td>Flux density - The measure of the rate in which radiative energy is</td>
<td>$S_{\nu}$</td>
<td>Some collected directly from catalogues. Other calculated</td>
<td>To calculate the radio luminosity of each</td>
<td></td>
</tr>
</tbody>
</table>


$^{83}$ Bennett, A “The revised 3C catalogue of radio sources”, MRA, 68, 1962, pp. 163


$^{85}$ Bennett, A “The revised 3C catalogue of radio sources”, MRA, 68, 1962, pp. 163

received from a source. using equation (1).

galaxy

<table>
<thead>
<tr>
<th>Co-moving distance ('proper distance') – the inflation of the universe is ignored and so this distance does not change with time.</th>
<th>D</th>
<th>Was calculated from the redshift using equation (2). A piece of python code was used to commute the value. See appendix.</th>
<th>Used with other values to calculate the radio luminosity of each galaxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio Luminosity</td>
<td>P_r</td>
<td>Was calculated using the flux density, comoving distance and redshift using equation (3).</td>
<td>Used to compare different luminosities with different morphologies. Also meant control samples could be made with similar</td>
</tr>
</tbody>
</table>

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BH mass $M_{\text{BH}}$ Collected from literature. Used to compare with control samples. Also used to test merger theory in x-shaped galaxies.

Eddington Ratio $L_{\text{bol}} / L_{\text{Edd}}$ Collected from literature Used to study accretion rates in young galaxies as $L_{\text{Edd}}$ is proportional to the maximum accretion rate.

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Table (1): The parameters used in the project and how they were collected and used in this investigation.
So the radio luminosity of each galaxy can be calculated, first the spectral index, $\alpha$, needed to be calculated from the data collected. The following relation was used:

$$\alpha = \frac{\Delta \log(S)}{\Delta \log(v)}$$

*Equation (1)*

Python was set up with the cosmolpy environment and some code was used (see appendix 1) to take the redshift of all the galaxies, and use the below equation to calculate the co-moving distance ($D$)\textsuperscript{92}:

$$D = \frac{C}{H_0} \int_0^z \frac{dz'}{\sqrt{(\Omega_m(1 + z')^3 + \Omega_k(1 + z)^2 + \Omega_\Lambda)}}$$

Where $C = 18.97879$ \hspace{1em} $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ \hspace{1em} $\Omega_m = 0.3$, $\Omega_k = 1$ and $\Omega_\Lambda = 0.7$

*Equation (2)*

With both these numbers calculated for the galaxies, they were then used in the below equation to calculate the luminosity ($\log P_v$) of the galaxies.

$$\log P_v = \log S_v + 2 \log(D) + (1 - \alpha) \log(1 + z) + C$$

*Equation (3)*

**Morphology**

Morphologies for most of the radio sources in the sample were obtained from the results of published work. However, for sources where a definite morphological classification could be found, radio contour plots were obtained from the NASA virtual observatory Skyview. For each unclassified galaxy, the NVSS and FIRST radio contour plots were inspected.

<table>
<thead>
<tr>
<th>Morphology</th>
<th>NVSS and FIRST outcome</th>
<th>Figure/Appendix/reference</th>
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<tr>
<td><strong>FRI</strong></td>
<td>Sources with collimated jets showing hot spots near the core and jets.</td>
<td>The regions of highest surface brightness are located along the jets.</td>
</tr>
<tr>
<td><strong>FRII</strong></td>
<td>Extended radio lobes (NVSS), compact cores and hotspots (FIRST).</td>
<td>FIRST contour plot of a characteristic example of an FRII source, 3C 223. The hot spots are located at the ends of the aligned lobes.</td>
</tr>
<tr>
<td><strong>Compact</strong></td>
<td>Sources of size</td>
<td></td>
</tr>
</tbody>
</table>
smaller than 5 arcsec or previously classified as QSOs were classified as ‘compact’

| Uncertain | Sources for which the FRI/FRII classification was impossible to decide, mostly due to poor resolution, were classified as ‘uncertain’ and not used in the sample. | Disturbed morphology or with angular size too small to classify |

Table (2): How sources were classified by their morphology
Results, Analysis and Discussion

Diagram(1): A histogram showing the spectral index ($\alpha$) of every RG in this project.

Table(3): Averages and standard deviations for the spectral indices

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRI sources</td>
<td>-0.64</td>
<td>0.30</td>
</tr>
<tr>
<td>FRII</td>
<td>-0.82</td>
<td>0.22</td>
</tr>
<tr>
<td>Compact</td>
<td>-0.46</td>
<td>0.43</td>
</tr>
<tr>
<td>X-shaped</td>
<td>-0.76</td>
<td>0.16</td>
</tr>
</tbody>
</table>

All Sources - Spectral index distribution

$\alpha = \frac{\Delta \log(S)}{\Delta \log(v)}$
The index distribution of the FRI and II sources peaks at values which are lower than that of the compact sources (*see diagrams 4-7*). This indicates the steep-spectrum nature of extended sources. There is also a difference in spectral index distributions between the FRI and FRII with the FRI having a higher mean and median $\alpha$ than the FRII. This could be explained by the fact that higher luminosity sources have lower values of $\alpha$ for extended radio sources (FRI tend to have lower luminosity than FRII). Known as the P-$\alpha$ effect – it is due to extraneous synchrotron losses for sources with greater power.
Diagram (8): A histogram showing the radio luminosity ($\log P_{1.4\text{GHz}}$) distribution for all sources.

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Average $P_{1.4\text{GHz}}$ [W Hz$^{-1}$ sr$^{-1}$]</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRI sources</td>
<td>27.11</td>
<td>0.87</td>
</tr>
<tr>
<td>FRII</td>
<td>28.76</td>
<td>0.86</td>
</tr>
<tr>
<td>Compact</td>
<td>29.30</td>
<td>0.83</td>
</tr>
<tr>
<td>X-shaped</td>
<td>28.15</td>
<td>0.57</td>
</tr>
<tr>
<td>DDRG outer lobe</td>
<td>28.39</td>
<td>0.72</td>
</tr>
<tr>
<td>DDRG Inner lobe</td>
<td>26.70</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Table (4): Averages and standard deviations for the luminosity.
Diagrams (9) and (10): A histogram showing the radio luminosity ($\log P_{\text{1.4GHz}}$) distribution for FRI and FRII sources

The FRI and FRII luminosity distributions for sources in all the samples are shown above. They show clearly the fact that the distribution of FRI sources tend to peak at lower luminosities than the FRII sources do (see diagrams 9 and 10). This being the case luminosity cannot be systematically used to classify RG; there is a large overlap between the luminosities distributions.
Diagram (11): A histogram showing the radio luminosity ($log P_v$) distribution for compact sources

The compact sources have a higher average luminosity than the other radio sources. This was to be expected as around 40% of all powerful radio sources are made up from either GPS or CSS sources.

Diagram (12): A histogram showing the radio luminosity ($log P_v$) distribution for X-shaped sources

It was found that the average 1.4 GHz luminosity of $log L [W/Hz^2sr^{-1}] = 28.16$. As X-shaped radio sources are known to have radio luminosities close to the FRI/FRII divide, this was as expected. The connection to the FRI/FRII divide is unclear although it would be very tempting to try and associate this with their transitory appearances. It is possible that the X-shaped galaxies are transitory objects between
the FRI and FRII, but before this could be proven more data will need to be collected. There are 100 possible candidate x-shaped galaxies, but only some are confirmed.

To pursue this association further, X-shaped sources with a larger range of luminosities will need to be confirmed and studied. It could be that the radio luminosity dividing the FRI and FRII morphology sources is dependent on the parent host galaxy magnitude over a comparable radio luminosity range\textsuperscript{93}. By undertaking further radio imaging of these x-shaped galaxies a dedicated host-galaxy imaging program could be used to determine the proper placement of X-shaped radio sources in the , which could help to understand the physical origin of these galaxies.

A DDRG has a core surrounded by a pair of double radio sources with an edge-brightened radio morphology – similar to a FRII. It is possible that some DDRG’s newly-formed jets may propagate outwards through debris left over from the old, relic galaxies, rather than the IGM. Most of the galaxies in our sample have outer lobe sizes of around 1 Mpc. In the sample some of the DDRGs had an inner lobe luminosity which was similar to ones found for the FRIs, even though they showed radio contours that looked more similar to a FRII.

Diagrams (13) and (14): A histogram showing the radio luminosity (log $P_r$) distribution for both outer and inner lobes in a DDRG
This could be interpreted as an earlier cycle of activity and a possible relic source which can occur after galactic mergers\textsuperscript{94}.

Each DDRG in our sample had outer lobes which could be classed as FRII. The inner pairs of lobes for our sample do not seem to fit easily into a category.

It could be suggested that the inner lobes are there due to emission of electrons at relativistic speeds within the outer lobes. The electrons undergo compression and are accelerated again by jets restarting within the outermost lobes\textsuperscript{95}. Eventually a hotspot could develop on the edge of the outer lobe which would give the DDRG the appearance of a FRII galaxy.

This could suggest that DDRGs are an intermediate phase and just a part of the evolution of large-scale RG. The inner pair of lobes in each DDRG could suggest that there is a second episode of jet activity.

\begin{footnotesize}

\end{footnotesize}
Diagrams (15) – (18): A histogram showing the black hole mass distribution for compact sources

Table (5): Averages and standard deviations for the black hole mass of compact sources

<table>
<thead>
<tr>
<th></th>
<th>Average black hole mass (M$_{\odot}$)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS</td>
<td>8.32</td>
<td>0.79</td>
</tr>
<tr>
<td>GPS</td>
<td>8.24</td>
<td>0.54</td>
</tr>
<tr>
<td>All sources</td>
<td>8.28</td>
<td>0.62</td>
</tr>
</tbody>
</table>

For compact sources it was found that the BH mass averages are lower than other documented RG, but it has also been estimated that younger RG have a lower BH mass than their older counterparts. This could be due to the fact that they have not
yet under gone major mergers and lack the necessary inwards forces in the central engines and are still early on in the accretion process. Young RG have previously had BH masses to be estimated of around log\(M_{bh} = 8.3\) \(M_\odot\).\(^{96}\) Typical broad line RG and NLS1s show Eddington ratios of around -1.10\(^{97}\) and 0.8\(^{98}\) respectively. Hence our sample shows an average more similar to the NLSI galaxies.

**Diagrams (19) – (22): A histogram showing the Eddington ratio distribution for X-shaped sources**

---


<table>
<thead>
<tr>
<th>Source</th>
<th>Eddington ratio</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS</td>
<td>-0.59</td>
<td>0.82</td>
</tr>
<tr>
<td>GPS</td>
<td>-0.58</td>
<td>0.29</td>
</tr>
<tr>
<td>All sources</td>
<td>-0.58</td>
<td>0.72</td>
</tr>
</tbody>
</table>

*Table (1): Averages and standard deviations for the Eddington ratio of compact sources*

During the early stages of accretion activity in a RG the BH is growing at a fast rate. The BH in the centre of young galaxies may still be collecting mass. This could be because the young RG are only in the early stages of both jet production and the accretion process. The averages calculated in this project are that lower average found on a similar investigation. One reason to explain this could be that this projected looked at both GPS and CSS sources, whilst the other one only CSS sources. A more complete and larger sample containing more BH mass and Eddingtons ratios would be needed in order to extend this work further.

---


The distribution of the BH mass for the X-shaped sources

The distribution of the BH mass for the control sample sources

The distribution of the BH masses for the X-shaped sources and Control


<table>
<thead>
<tr>
<th></th>
<th>Average log ( M_{\text{bh}} ) (( M_\odot ))</th>
<th>Average ( M_{\text{bh}} ) (( M_\odot ))</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-shaped</td>
<td>8.63</td>
<td>( 4.24 \times 10^8 )</td>
<td>0.45</td>
</tr>
<tr>
<td>Control sample</td>
<td>8.32</td>
<td>( 2.07 \times 10^8 )</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table (6): Average and standard deviation for the BH mass of X-shaped sources and the control sample

The mean mass of the BHs of the X-shaped galaxies in the sample is found to be higher than that calculated for the control sample. In fact the average BH mass of the X-shaped galaxies in our sample is around twice the average of the BH mass for control sample. The strange x-shaped morphology is said to come from the
reorientation of the jets\textsuperscript{101} or from there being two active BH after a galaxy merger. It is suggested that mergers produce elliptical galaxies where both the galaxies had a similar mass\textsuperscript{102}. This could suggest the possible presence of two central engines in the centre of X-shaped radio sources and could be used in support of the theory that X-shaped radio sources contain two SMBHs or were formed during a merger of two SMBH.

As this project used data from different sources it is important to note that in some cases conflicting data was collected for the same source. Some of the sources had classified RG differently, some were FRI in some whilst FRII in another for example. It was also hard to get complete data sets for all the galaxies. Some catalogues which had focused on the FRI/FRII dichotomy would have loads of morphological data, but had little optical data or other quantities in order to derive the black hole mass. On the other hand, the literature that had concentrated on the central engines proprieties, usually was on a smaller scale.

Some of the samples we have taken sources from are flux-limited. In cases like this, the lowest luminosity objects (in this case the FRI) are naturally selected out. This makes it important to confirm if some of the less luminous, more centrally peaked radio galaxies do indeed have FRI radio morphology. Unfortunately, as these are not yet optically classified they are very faint and have smaller angular size, so it would be a difficult task.


\textsuperscript{102} Y. H. Wen, Z. L. Wen, J. L. Han, L. G. Hou “Influence of major mergers on the radio emission of elliptical galaxies”, A&A, 542, 2012, pp. 4
Conclusion

This project calculated the luminosity for a large number of RG. Compact sources were found to have a higher average luminosity than the others in the sample – which was expected as compact sources make up around 40% of all powerful radio sources. The central engines of these galaxies were investigated and it was found that the average BH mass is lower than other RG, and the suggested reason for this was they had yet to undergo major mergers and lack the necessary inwards forces in the central engines and are still early on in the accretion process.

The results from this project show the expected luminosity difference in relation to the FRI/FRII dichotomy. It has been discussed how FRIIs can take several different evolution paths before becoming a FRI and how different starting conditions for the central engines play a big part in the evolution.

When a minor merger occurs between two galaxies with similar masses, the FRII in these cases evolve into FRIs before the interaction between the accretion disk and BBHs has chance to get started. The galaxies involved here spend the shortest time in the FRII phase and are shorter than other FRIIs. Where in major mergers, the FRII evolve over longer timescale, allowing the BBH and the accretion disk a chance to react and eventually result in FRI galaxies with more luminous jets than the first example.

The last option put forward was that the FRII galaxies evolved into an intermediate phase before finally evolving into a FRI. FRI in this scenario form after the merger of SMBBH. It has been suggested here that after the binary plane, outer accretion disk and the galactic plane become coplanar, that FRIIs could evolve through an intermediate phase with showing an X-shaped or DDRG morphology. DDRG and X-shaped galaxies are believed to be signs of episodic activity.

Each DDRG in our sample had outer lobes which could be classed as FRII. The inner pairs of lobes for our sample do not seem to fit easily into a category. This could be interpreted as an earlier cycle of activity and a possible relic source which can occur after galactic mergers - This could suggest that DDRGs are an
intermediate phase\(^{103}\). The idea of relic sources was discussed and the limitation of outer lobes in some sources, being aligned with the inner lobes.

The results from this project calculated the average BH mass of X-shaped galaxies to be double that of the control group. It suggested the possible presence of two central engines in the centre of X-shaped radio sources and could be used in support of the theory that X-shaped radio sources contain two SMBHs or was formed during a merger of two SMBH.

The radio source 3C75 could be used as observational evidence of this process. 3C75 is found at the centre of an Abell cluster of galaxies and the unusual intertwined jets and plumes emanate from a double nucleus. Initially this was thought to be a single galaxy with a BBH but further optical studies showed that in fact there was a pair of elliptical galaxies each with its own BH. The two galaxies have yet to fully merge but are interacting with each other\(^{104}\). We could here be seeing a snapshot of the radio evolution process. The merger that we appear to be seeing here could be the driving force in RG evolution.

CGCG 292−057 is the host RG to both DD and X-shaped radio sources. CGCG 292−057 is another snapshot of galaxy evolution and we can investigate galactic mergers, episodic jet activity and reorientation over short time-scales\(^{105}\). There has also been evidence found suggesting galaxy merger as tidal features and tails are seen\(^{106}\). The highly polarised outer lobes seen in this galaxy are what we would expect from an X-shaped galaxy.

The X-shaped morphology could be explained by the SMBH realigning and subsequent interactions with the accretion disc. Another explanation is that in a minor merger one BH would move towards the other, getting gaps in the accretion disk in the process. After the BBH has completely merged, the holes in the disk grow, which temporarily ceases the formations of jets. The newly formed BH with high mass attracts an inflow of matter which allows jet activity to form. The distribution of orientation for the jets is random and this is due to the merging


galaxies impacting randomly. It is possible that DDRG and X-shaped are showing a SMBBH merger at different phases.

X-shaped galaxies and DDRG are a useful way to study galactic evolution and there are still many unanswered questions. Why are there so few X-shaped galaxies? After jet formation ceases what happens to the radio lobes once their energy is cut off? More studies into DDRGs outer lobes could yield answers as they are probably in an evolutionary stage. Does the IGM have an impact on these, or is it only the jet material which is contributing? What time-scales do these processes occurring on? Further insight into these galaxies could help us to understand more about galactic evolution.
References


Bennett, A “The revised 3C catalogue of radio sources”, *MRAS*, 68, 1962, pp. 163


Chen, Xian; Liu, Fukun “Relationship between X-shaped radio sources and double-double radio galaxies” *Black Holes from Stars to Galaxies Proceedings of the International Astronomical Union* 2007 238 pp. 341-342


Gendre, M. A.; Best, P. N.; Wall, J. V.” The Combined NVSS-FIRST Galaxies (CoNFIG) sample - II. Comparison of space densities in the Fanaroff-Riley dichotomy”, *MNRAS*, **404**, 2010, pp. 1719-1732n


Wu Q W., “The black hole mass, Eddington ratio, and $M_{bh}-\sigma_{[OIII]}$ relation in young radio


Appendix

Python was set up with the Cosmolopy\textsuperscript{107} and SciPy (a library of scientific and numerical routines) and below is an example of the code used to calculate the co-moving distance in Mpc for a given redshift, $z$

```python
>>> d_co: ndarray
>>> import cosmolopy.distance as cd
>>> cosmo = {'omega_M_0' : 0.3, 'omega_lambda_0' : 0.7, 'h' : 0.72}
>>> cosmo = cd.set_omega_k_0(cosmo)
>>> d_co = cd.comoving_distance(6., **cosmo)
>>> print "Comoving distance to z=6 is %.1f Mpc" % (d_co)
Comoving distance to z=6 is 8017.8 Mpc
```

\textsuperscript{107} Cosmolopy package: http://roban.github.com/CosmoloPy/docAPI/cosmolopy-module.html