

Understanding the Fanaroff-Riley radio galaxy classification

L. Saripalli

Raman Research Institute, Bangalore, India

lsaripal@rri.res.in

ABSTRACT

The simple, yet profoundly far-reaching classification scheme based on extended radio morphologies of radio galaxies, the Fanaroff-Riley classification has been a cornerstone in our understanding of radio galaxies. Over the decades since the recognition that there are two basic types of radio galaxy morphologies there have been several findings in different wavebands that have reported properties on different scales. Although it is realized that there may be intrinsic as well external causes an overarching view of how we may understand the two morphological types is missing. With the radio power-absolute magnitude relation (the Owen-Ledlow diagram) as backdrop we review and develop an understanding of the two radio galaxy types in the light of what is known about them. We have for the first time included the dust properties of the two FR classes together with the relative orientations of dust, host major axis and the radio axis to present a qualitative framework within which to understand the conditions under which they form. We discuss how the host elliptical and its history can explain the distribution of radio galaxies in the Owen-Ledlow diagram. Mass of the host elliptical galaxy is a crucial player in deciding what type of a radio galaxy it can host in what conditions. Benign conditions, characterized by natural evolutionary processes, most easily give rise to FR-I type sources in ellipticals of all mass regimes where as with FR-IIs we reason that it is hard to form them without mergers. In undisturbed conditions elliptical galaxies appear to acquire stable states where the black hole axis settles along the host minor axis. With the steady conditions and the continuous supply of ambient gas, the FR-Is in principle, may be powered for a long time. Aided by mergers and interactions low mass ellipticals more easily form FR-II type sources than more massive hosts. LEG FR-IIs may include dying as well as restarted FR-II radio galaxies.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: active — radio continuum: general — galaxies: jets — galaxies: nuclei

1. Introduction

Although radio galaxies come in a variety of morphologies a basic division in structural types has stood the test of time: the Fanaroff and Riley classification (Fanaroff & Riley 1974). It was based on the recognition that radio sources often came in two flavours, those having edge-darkened (FR-I) morphologies and those having edge-brightened (FR-II) morphologies. The division was based entirely on radio structures that exist on large scales from few to several hundred kiloparsec to several megaparsec. That the two radio morphologies also divide on the basis of sev-

eral other properties both on large scale and small points to more fundamental processes at work that can have profound effect on what type of structures form on large scales.

Since the time of this simple classification scheme there have been several attempts to understand how these two basic morphologies arise. Building on the basic models of Blandford & Rees (1974), Scheuer (1974), and Falle (1991) there are detailed models today that are able to reproduce with fair consistency data gathered on these source populations (Kaiser et al. 1997; Blundell et al. 1999). At the heart of any model

that seeks to reproduce the large scale radio structures is the basic tenet of interaction between a jet and its ambient medium. The interplay between the two under varying characteristics of the jet and the external medium through which it propagates is shown to produce the two types of structures. Although other source morphological types have been discovered they have usually been understood within the Fanaroff-Riley classification.

While the two types of radio structures are understood as arising out of the different interactions that low and high power jets have with the environment (Scheuer 1974; Bicknell 1986) a basic question remained however as to whether the two source types were intrinsically the same or different: could the FR-Is and FR-IIIs be the consequence as well of very different central engines and host galaxies or the consequence entirely of the different interactions with the environments?

Over the several decades a number of multi-wavelength studies on FR-I and FR-II radio sources has gathered a variety of data on these sources testifying to the importance of the question lying at the focus of these efforts. Several important findings related to the two categories of sources were reported. A picture is emerging which highlights the intimate connection between the elliptical galaxy and the radio galaxy it hosts, where there is a dynamic relationship between them and where the history of the host galaxy has an important role.

In this paper we develop a framework that brings together some key research in this area that was not considered earlier. There have been efforts in the past, particularly the work of Baum et al. (1995) who have put forward a scenario for forming the two types of radio galaxies. We make use of their research as well as more recent findings in our effort to present a coherent picture in which we may understand the conditions in which the two basic morphological types form. We summarize some of the key observations of FR-Is and FR-IIIs in section 2 after which in sections 3–6 we introduce and examine properties of FR-Is and FR-IIIs not considered earlier, which we now incorporate within our framework. In section 7 we present and discuss the framework where due attention is given to the insightful Owen-Ledlow diagram (Owen 1993; Owen & Ledlow 1994) and the crucial role it has in the effort to understand radio

galaxies. This is followed by the summary.

2. A summary of some key findings on FR-Is and FR-II radio galaxies

In this section we list some of the well-known and well-used findings reported for the two classes of radio galaxies. Right in the seminal paper recognizing the two radio source morphologies, Fanaroff & Riley (1974) pointed out the correlation of the morphologies with the total radio power: the two morphologies are divided in their total radio power with the edge-darkened FR-I type radio galaxies having lower radio powers and the edge-brightened FR-II type radio galaxies having higher radio powers. The two radio source types were found to be divided at the so-called dividing power of $10^{25} \text{ W Hz}^{-1}$ at 1.4 GHz.

FR-Is and FR-IIIs also compare interestingly with respect to their environments. At nearby redshifts ($z < 0.5$) while the FR-Is are found to be located in dense environments (galaxy clusters) the FR-IIIs are often found to be hosted by field galaxies. At higher redshifts though both FR-I and FR-II type radio sources are found in rich environments (Hill & Lilly 1991). The elliptical galaxies that host the two FR types were also found to show differences. Broad band imaging of the host galaxies showed that hosts of FR-IIIs were found to be bluer than hosts of FR-Is and often showed signatures of mergers (Heckman et al. 1986; Smith & Heckman 1989; Baldi & Capetti 2008; Ramos-Almeida et al. 2012). Then again the host galaxies of FR-Is were found to be more massive than the FR-II hosts (Owen & Laing 1989; Govoni et al. 2000). While AGN optical spectra of some of the FR-II hosts showed emission lines this was almost never the case in FR-I optical spectra. We will return to this topic of AGN spectra later in this section.

One of the important developments in this area has been the Owen-Ledlow diagram (Owen 1993; Owen & Ledlow 1994) where the two source types divide about a line with slope of about 1.8 in the total radio power-absolute optical magnitude plane. The dividing power, hitherto believed to be fixed was instead found to be increasing with the host optical luminosity. If FR-I structures are a result of jets that are affected by entrainment, instabilities and turbulence then one could under-

stand the increasing dividing power with absolute host optical magnitude as galaxies with jets that found it increasingly difficult to remain collimated and supersonic as the ambient medium became denser (Bicknell 1995). This dependence of the FR-I/II dividing power on the host absolute magnitude put the spotlight on the role of environment in producing the two different radio source morphologies.

The finding of a hybrid morphology in some radio galaxies, with one lobe being edge brightened and another edge darkened (Gopal-Krishna & Wiita 2000) strengthened the view that environment in which the jets propagated were ultimately responsible for the kind of structure that developed on large scales.

With the increasing availability of high resolution optical imaging as well as more complete optical spectroscopic observations, details with respect to the AGN as well as host galaxy characteristics on more global scales emerged that had to be understood.

The study noting differences in optical spectral properties of FR-I and FR-II hosts reported by (Hine & Longair 1979) was followed by works that used classifications based on spectral line ratios (Baum et al. 1992; Laing et al. 1994; Tadhunter et al. 1998; Chiaberge et al. 2002; Buttiglione et al. 2010) which clearly showed that the two morphological types exhibited different behaviour. While FR-I radio galaxy hosts always exhibit optical spectra with only absorption lines or $O[III]/H\alpha < 0.2$ (low ionization emission line radio galaxies, LEGs, following the definition of Laing et al.), the FR-II hosts were of mixed category. Some FR-II hosts were like FR-Is with either only absorption lines or prevalence of low ionization emission lines with low $O[III]/H\alpha$ ratios but some others showed spectra with strong high ionization emission lines with $O[III]/H\alpha > 0.2$ (high ionization emission line radio galaxies, HEGs).

Baum et al. (1992) found clear differences in the characteristics of the emission line gas in the two FR types. Most FR-IIs appeared to have rotating disks of line-emitting gas on large scales up to 15 kpc that also sometimes included disks with chaotic and turbulent motions which contrasts with those in FR-I type sources. These findings were linked with two different modes of gas acquisition for fueling the AGN in the two FR types.

The quite different emission line characteristics of FR-I and FR-II radio galaxies led Baum et al. (1995) to explore different ways of producing the two morphologies. A preferred model was that the differences arose in the different accretion rates: low accretion rates in FR-Is and high accretion rates in FR-IIs. Differences in the black hole spin too was suggested for the two classes with FR-Is having a lower black hole spin. Marchesini et al. (2004) also found that the accretion rates needed in FR-Is were very low, less than ~ 0.001 in Eddington units. However again interestingly the FR-IIs appeared to span two regions, one that had similarly low accretion rates as FR-Is and a small fraction that required higher accretion rates.

X-ray and IR observations (Hardcastle et al. 2007) and references therein and Best & Heckman (2012)) and the optical spectroscopic studies (Buttiglione et al. 2010; Mahony et al. 2011) further support and highlight the division based on line ratios (LEG and HEG type) and the link with accretion mode and source of fuel. Increasingly it is being suggested that the two optical spectral classes are powered by two different accretion modes and fuel sources: radiatively inefficient low accretion rates sourced from hot gas accretion that powers the low and high power LEGs where as radiatively efficient high accretion rates sourced from cold gas accretion powering the HEG sources. The hot gas is suggested as originating from the hot coronae of the hosts and from the stellar mass loss from the stars in the galaxy. On the other hand the cold gas is suggested as originating from a gas-rich merger with another galaxy.

High resolution optical imaging with HST revealed the prevalence of nuclear optical cores in both FR-Is and FR-IIs (Chiaberge et al. 1999, 2000, 2002). However there were clear differences between the two FR types, with a clear correlation seen between the optical core powers and the radio core powers for the FR-Is and a more complex behaviour for the FR-IIs. While the FR-Is were inferred to have unobscured, radiatively inefficient accretion disks the FR-IIs once again divided into two distinct types: a population that showed similar properties as the FR-Is (constituted by the LEG FR-IIs) and a population constituted by the HEG FR-IIs where presence of dust torii and radiatively efficient accretion disks were inferred.

In the following sections we look at some addi-

tional properties of the two FR types where they show differences and we try to develop a framework inclusive of these findings. We first consider the dust characteristics of the hosts of the two FR types.

3. Dust and FR classification

More than three decades ago Kotanyi & Ekers (1979) reported the perpendicularity of dust distribution and radio axes for a small sample of radio galaxies. At that time the sources involved only the nearby galaxies with prominent dust distributions. It was also the case that the radio sources were mostly FR-I radio galaxies. With the HST making possible the high resolution imaging of galaxies, dust on much smaller scales was revealed and in particular dust distributed in the nuclear regions.

van Dokkum & Franx (1995) and Verdoes Kleijn & de Zeeuw (2005) used archival HST data to study dust in elliptical galaxies. They reported a high prevalence of dust among the hosts of radio galaxies as compared to normal ellipticals that suggested a link between dust and nuclear activity. Differences in properties were seen for dust on small ($< 250 pc$) and large scales ($> 250 pc$). The only dust features to show kinematic coupling with the stars were those on small scales (4 out of 7; Fig. 7; van Dokkum & Franx (1995)) where as large scale dust showed no such kinematic coupling. Large scale dust (and at least some small-scale dust) therefore carry signatures of angular momentum different from that of the host ellipticals and indicate external origin, perhaps in mergers. Mostly consistent with the differences are the properties of appearance and location of the dust on large and small scales. The dust on large scales generally had an irregular appearance and was distributed uniformly with respect to the major axis where as the dust on smaller scales was mostly of regular, relaxed appearance and was located on the projected major axis of the host galaxy (van Dokkum & Franx 1995; Verdoes Kleijn & de Zeeuw 2005).

de Koff et al. (2000) and de Ruiter et al. (2002) used HST observations of two well-known and well-imaged (both in radio and the optical) radio galaxy samples (the 3CRR and B2 samples respectively) to study the dust characteristics of the

radio galaxy host ellipticals. These observations revealed the very different dust characteristics of the two FR types.

While both de Koff et al as well as de Ruiter et al reported the trend for the dust to be distributed perpendicular to the radio axis it was found to be the case predominantly for the FR-I radio sources. The FR-IIs on the other hand showed less or no tendency for perpendicularity. The dust in FR-Is was mostly seen in the form of small regular circumnuclear dust lanes or disks where as the dust in FR-IIs had varied morphology and extent. Both also reported the lower dust masses among FR-Is as compared to FR-IIs. Interestingly, de Ruiter et al. (2002) noted that the perpendicularity between the radio axis and dust is confined to lower power FR-Is, becoming weak or absent in stronger FR-Is. de Koff et al. (2000) noted that in FR-IIs dust-radio perpendicularity was seen only when dust was 'concentrated close to the nucleus'.

While the dust-radio axis relation and dust characteristics such as appearance and size have been examined in all the above works, the location of the dust (perpendicular to the radio axis) with respect to the host major axis got little attention except in the work on normal and FR-I ellipticals by Verdoes Kleijn & de Zeeuw (2005). Their Fig. 4 shows that in several cases where the dust is perpendicular to the radio axis it lies within 25 degrees of the host major axis (8 out of 14 sources). The coincidence with the major axis is even more impressive when only smooth, regular dust ellipses are considered (6 out of 7 sources). The persistence of dust-radio perpendicularity even when dust does not lie on the host major axis, as seen in some of the cases, is also reported by van Dokkum & Franx (1995) (in Fig. 8) where although the dust is perpendicular to the radio axis in 6 galaxies (admittedly, a rather small sample) it lies on the host major axis in only half the sources.

We point out that the detection as well as appearance of the dust features will depend on distance to the source. Since FR-Is and FR-IIs are generally selected from different redshift regimes (FR-Is near and FR-IIs far) could the differences in dust characteristics of the FR-types be attributed to distance related effects?

The dust characteristics of radio galaxies

being discussed here have been sourced from mainly three previous works, de Koff et al. (2000), de Ruiter et al. (2002) and Verdoes Kleijn & de Zeeuw (2005). All three authors have endeavored to study the effect of distance on their findings. Little effects of distance are found for radio power-dust mass relation or dust morphologies, classification, or position angles.

To collect together the points relevant for the dust-radio axis perpendicularity relationship, it appears that the relation is strongest for lower power FR-Is with jets rather than for FR-IIIs and that dust need not always lie on the host major axis.

As for the dust in elliptical galaxies, without concerning ourselves with whether it hosts a radio galaxy or not, it seems that dust can exist on large scales and small scales and the morphologies of the dust on the two scales is different. The dust on large scales is mostly unsettled where as dust on small scales appears mostly regular and settled. The division of large-scale dust and small-scale dust seems to largely adhere to the division of the FR type with FR-II radio galaxies associated with dust on large scales and FR-I radio galaxies with dust on small scales.

Dust however is clearly found to be important for the AGN activity and the dust mass is clearly found to be related to the radio power with increasing dust mass for higher power radio galaxies going from low power FR-Is, high power FR-Is and to the FR-IIIs.

Table 1 puts together the dust properties of FR-I and FR-II sources.

Therefore there is a clear division seen among the dust characteristics of the two FR types. Any framework for understanding the FR categories needs to consider these rather stark differences. The dust properties appear linked to the kind of radio morphology that emerges on tens to hundreds of kpc scales.

If dust properties on global scales are found to be related to the manner of manifestation of the twin jets from the central engine, whether an edge-darkened or edge-brightened extended radio source results, it is worth examining if dust origin can be linked to the formation of the two source types.

4. Relative orientations of radio and host optical axes and the FR classification

Saripalli & Subrahmanyan (2009) studied the relative orientations of radio and host optical axes of the 3CRR FR-II sample and found that there was no preferred relation; the radio axes are distributed over a wide range of angles from 0 to 90° with respect to the major axes. Several previous studies also reported the same lack of relation between the radio and host optical axes for FR-IIIs (Palimaka et al. 1979; Guthrie 1980; Sansom et al. 1987). Curiously, it was only more recently that this study was performed for FR-I type radio galaxies. Browne & Battye (2011) used a large sample of FIRST radio sources identified with SDSS galaxies for which they derived the radio and host optical axes orientations and they reported a strong tendency for radio axes in their (largely FR-I radio galaxies) to be oriented along the host minor axis. Interestingly, this commonality of radio and host minor axes position angles is not shown by the stronger of their FR-I sources.

Once again these clear differences between the relative orientations of radio and host optical axes need to be brought within any wider framework seeking to understand the two FR types.

5. The host galaxies of FR-I and FR-II radio galaxies

Elliptical galaxies have been the subject of numerous studies. Given that they form the hosts of radio galaxies it is only natural to examine some of the recent detailed observations of this family of galaxies for any bearing they may have on the formation of the two radio galaxy types. While we do not attempt to summarize the body of data gathered on elliptical galaxies we use some of the more recent detailed observational studies to highlight aspects that clarify the characteristics of radio galaxy hosts. It is now well established via a number of works that elliptical galaxies fall into two categories: the fast rotators and the slow rotators (Emsellem et al. (2007), Kormendy (2009) and references within). These two classes of ellipticals have distinct properties in several respects. Of relevance to the hosts of radio galaxies we note that the dividing optical luminosity for the fast and slow rotators is at $M_b = -20.5$ with slow rotators being more luminous. With the hosts of

TABLE 1
SUMMARY OF DUST PROPERTIES OF FR-I AND FR-II SOURCES

| FR-Is | FR-IIs |
|---|---|
| Distributed on small scales ($< 250pc$) | distributed on large scales ($> 250pc$) |
| Circum-nuclear | not circum-nuclear |
| Sharp, disk-like | irregular and filamentary |
| Mostly on the host major axis | no relation with the host major axis |
| Small dust masses | large dust masses |
| Perpendicular to radio axis | no relation with radio axis |

radio galaxies predominantly being as bright or brighter than $M_b = -20.5$ it appears that most of the radio galaxy hosts fall in the group of slow rotators. This is supported by two other properties of radio galaxy hosts: their ellipticities and masses. Slow rotators are found to have ellipticities flatter than 0.3 which is also the range estimated for a large fraction of 3CRR host ellipticals (Saripalli & Subrahmanyan 2009). Moreover the slow rotators are also the more massive with masses larger than $10^{11}M_{\odot}$ which is also the mass regime for radio galaxy hosts.

There are several other distinctive characteristics of the two groups of ellipticals but we confine ourselves to the recognition that the hosts of radio galaxies resemble to a fair extent the slow rotating, massive elliptical galaxies. While this galaxy group is not as strongly oblate as the fast rotators the difference in the position angle of the photometric and kinematic axes is mostly within 20° for the sample studied by Emsellem et al. (2007) with as many as half having values within 10° (their Figure 4). It is reasonable to expect that a large fraction may be close to being oblate although there are clearly known triaxial galaxies.

6. In Perspective

We now attempt to put the dust properties of FR-I and FR-II sources in perspective. First, the scale lengths that we are dealing with regarding the dust on one hand and the location of the jet origin and hence the black hole spin axis are entirely different. As noted by van Dokkum & Franx (1995) one does not expect there to be any correspondence between the jet direction and the inflowing material considering that in the vicinity of the black hole frame dragging precesses the orbit of the incoming fuel. Even

with the resolution of the HST observations the seen dust is on scales nearly 7 orders of magnitude larger than the accretion disk scale. Yet it is with this large scale dust disk that a close relationship exists between it and the jet axis and that too predominantly only in FR-Is. Now, dust as we have seen is important for AGN activity. Dust exists also in FR-IIs and in fact dust masses in FR-IIs are found to be larger than in FR-Is. Although, as seen in section 5, the host ellipticals of FR-IIs and FR-Is are similar, having similar range of absolute magnitudes and ellipticities yet the dust in FR-Is can appear different and also behave differently in its relationship with the radio axis: we need to understand why FR-Is are being singled out for the *dust – radio perpendicularity* relation and why the dust appears different in FR-Is and FR-IIs. The reasons as to why the dust-radio axis perpendicularity exists were speculated upon by Verdoes Kleijn & de Zeeuw (2005). In attempting to understand the reason for the particular relationship preferentially shown by the FR-I radio galaxies and in particular the lower power FR-Is we will also need to understand why the correlation is weaker or not seen among the FR-IIs. We will address this in Section 7.

Then again, with regard to the radio-host major axis perpendicularity relation it is the FR-Is that show this and not the FR-IIs. If the host galaxies of the two FR types are similar sharing the same range of optical luminosities and ellipticities we need to understand why FR-Is are being singled out for the *radio – major axis perpendicularity*.

We may express in other words to say that predominantly in FR-Is there is some kind of equilibrium configuration set up between the host galaxy, the dust and the black hole at the centre. Whereas although hosted by ellipticals of similar type such an 'equilibrium' evades the FR-IIs. It appears that

more powerful the beams less are the equilibrium relations with the dust axes and host major axes respected.

Below we will attempt to understand the conditions that may be causing these differences between FR-Is and FR-IIIs.

7. Understanding the two source types

7.1. The Owen-Ledlow diagram

Bicknell (1995) developed the theoretical basis for the dependence of FR-I/II dividing power on the absolute magnitude of the host elliptical (the Owen-Ledlow diagram). The FR-I/II borderline jet energy flux (and hence total radio power) was related to the host optical magnitude through parameters that affected the jet propagation i.e. the central pressure. A given absolute optical magnitude of an elliptical galaxy (or a given mass of elliptical galaxy) has an ambient pressure which corresponds to a unique transition jet flux such that for higher ambient pressures (and hence for more luminous elliptical galaxies) the FR-I/II jet transition occurs at higher jet energy flux. There have been other attempts to relate the jet advance with the ambient medium within the host galaxy (for example, Kawakatu et al. (2009)) and also attempts to understand the Owen-Ledlow diagram by redrawing the relation in terms of intrinsic parameters: nuclear photoionizing luminosity versus the black hole mass (Ghisellini & Celotti 2001; Wold et al. 2007).

A point to note about the Owen-Ledlow diagram is the scatter along the Y-axis. One sees that no longer is it that a galaxy of a given optical magnitude and hence mass produces a radio galaxy of a fixed morphology or fixed power. It is exciting to note that galaxies of the same absolute magnitude can host FR-Is as well as FR-IIIs and also FR-Is and FR-IIIs having a range of different powers. It follows that under different conditions an elliptical galaxy can host an FR-I or FR-II or an FR-I of a different power and an FR-II of a different power.

The Owen-Ledlow diagram is a powerful representation of the story of radio galaxies, of the relation between the large scale radio structures and the galaxies that host them, revealing that for every host galaxy mass there is a threshold jet power which is needed to produce an edge-

brightened structure and that if conditions within change the same galaxy can host a radio galaxy of a different power or different morphology in its lifetime. The Owen-Ledlow diagram therefore incorporates within it the possibility of restarting of nuclear activity. We will see below that the simple diagram can also provide a platform for understanding various other findings related to the two morphological types.

The translation of FR classes along the Y-axis was already remarked on by Ledlow & Owen (1996) and Ledlow (1997) who pointed out that this could be suggesting possibility of a transition between the two populations. In their preferred scenario for understanding the two FR classes Baum et al. (1995) also pointed out that the differences in the black hole spins (with low spin for FR-Is and high spin for FR-IIIs) allowed for the possibility of transition from FR-II to FR-I type. Such a transition is not unreasonable to expect since radio galaxies have finite life times and the beam switch-off process occurs more likely over a drawn out period of time rather than abruptly (as also discussed in Saripalli et al. (2012)). Saripalli & Subrahmanyan (2009) invoked such an FR-II to FR-I transition in morphology to explain the five, restarted X-shaped sources that on one hand showed main-lobe, edge-darkened structures while exhibiting properties similar to the rest of the X-shaped source population all of which were of FR-II type. Indeed in using Monte-Carlo simulations to test whether observed samples of radio galaxies can be random selections of elliptical galaxies, Scarpa & Urry (2001) found that the two FR classes are hosted by ellipticals extracted from the same population. Also, the Owen-Ledlow diagrams of radio samples in later studies are not found to be as sharply divided between the two classes as originally found and there is non-insignificant number of FR-IIIs below the canonical dividing line (Ledlow & Owen 1996; Lin et al. 2010). These below-line FR-IIIs, that are also found to be compact in physical size, have been speculated as being FR-IIIs that are likely to evolve into FR-Is as their low power jets get frustrated in interactions with the ISM of the host galaxy (Kaiser & Best 2007). While these compact FR-IIIs may be low power and young radio galaxies there may also be, as found among the ATLAS-ESS sources (Saripalli et al. 2012), larger

FR-II sources that are either relic-type or even restarted FR-II sources (where the outer lobes have reduced in power; Thorat et al, in preparation). The existence of FR-I type sources, the intriguing FR-I quasars, lying above the dividing line has also been reported (Heywood et al. 2007). We discuss this in later in this section.

The growing impression therefore is of flexible physical conditions across both the absolute magnitude axis as well as the integrated (radio) power axis. FR-I/II radio galaxies can both be hosted by elliptical galaxies having a wide range in absolute magnitudes (or masses) within the massive galaxy regime and at the same time not only do both FR types occur in galaxies of the same magnitude but FR-II radio galaxies can have integrated powers that lie below the dividing line. While the transition jet energy flux could be unique to an elliptical galaxy of a given absolute magnitude it remains to identify the physical conditions as well as connection with galaxy mass which will determine the type of extended radio morphology that will result.

7.2. Host galaxy mass and the FR type

With the backdrop of the Owen-Ledlow diagram in mind we sketch the following scenario to understand the differences in the properties of FR-Is and FR-IIs. Massive elliptical galaxies will have enough stellar mass loss to sustain a radio galaxy (Di Matteo et al. 2003; Ho 2009). Massive ellipticals will therefore frequently host radio sources given the regular source of fuel. However because of the higher central gas pressures and more extended interstellar medium of more massive elliptical galaxies, most jet powers generated will find it hard to retain their thrust over long distances through the ISM (Bicknell 1995). Only the more powerful of jets will remain supersonic and form FR-II morphologies. The resulting morphologies will therefore tend to be dominated by FR-I rather than FR-II morphologies. Also high power jets (capable of negotiating successfully the increased ISM) may likely be less often produced than low power jets since such jets would require higher accretion rates than that generated 'in-house' (otherwise most ellipticals will be associated with FR-II sources) and in the case of massive ellipticals will likely need gas-rich mergers.

The inability of massive ellipticals to host FR-

II morphologies gets more and more aggravated with increased mass of the galaxies. This and the high frequency of association of massive ellipticals with radio sources is consistent with the finding by Best & Longair (2005) that the fraction of low power radio sources hosted by elliptical galaxies is high (as high as 30%) and this fraction increases with galaxy mass.

It follows that lower the mass of the host galaxy it gets easier to host radio galaxies with FR-II morphologies. Unlike the more massive ellipticals the ISM is less rich and less extended and the threshold jet power is lower. However, while there is still the stellar mass loss that is available as fuel, it is likely to be available at lower rates than in the more massive ellipticals resulting in only weak sources. Overcoming these lower threshold jet powers may not need a large jump in accretion rate however and they may relatively easily be breached by even small ingestions of external fuel. A dependable way for a lower mass elliptical to create radio galaxies having FR-II morphology is if this additional source of fuel comes in, say, through a merger.

Host galaxy mass and its history appear to be key to the type of extended morphologies that result on large scales. Since the galaxy mass correlates with the central black hole mass how do black hole mass differences bear on the two radio galaxy types? Black hole mass has a direct consequence to the Eddington accretion rate. With in-house accreted mass also scaling with the galaxy mass differences in the Eddington ratios could arise more from causes such as e.g. merger opportunities, active star-formation or environments.

7.2.1. *Understanding the dust characteristics of FR-Is and FR-IIs*

The reasoning given above accounts for several of the properties that are found for FR-I and FR-II radio galaxies. For example, with massive and mostly oblate type ellipticals more likely to be hosting FR-I radio morphologies it explains the large host masses reported for FR-Is. With stellar mass loss and the gas from the hot coronae being the predominant fuel source (Buttiglione et al. 2010) one expects that there is a regular supply of gas and dust. This dust shares the angular momentum of the stars in the galaxy and unless there is a merger it will make its way to the cen-

tre of the deep potential well unmolested. With the major axis plane being the equilibrium plane in oblate-type ellipticals the dust will tend to settle there where it can form stable closed orbits (van Dokkum & Franx 1995). The rate of supply of gas and dust is steady and is only as high as the rate at which the stars evolve or the coronal gas is ingested. This decides the upper limit to the disk accretion rate. The relatively low rates ensure low power jets which, given the high galaxy mass, will result in FR-I radio structures. Given the stable nature of the process of accumulation of gas and dust it will settle into a regular disk at the centre of the galaxy. Moreover the dust will get to be observed only when it has accumulated in sufficient amount which happens when it reaches smaller scales near the central regions. The internally originating dust is expected to be generated from regions uniformly distributed over the galaxy without having visible signatures such as clumps or disks or lanes and hence it will not be observed. Hence the correlation of dust morphology with location on small scales and location on the major axis. In such a picture, FR-Is are predominantly seen associated with massive ellipticals and without the need for mergers. We point out that this scale on which the dust is seen is still several orders of magnitude larger than the accretion disk in the vicinity of the black hole. In such a steady state within the galaxy where dust has been collecting at the centre for a long period the black hole would have been re-aligned perpendicular to the dust disk.

As for the FR-II sources, their hosts are more likely to be small and to have swathes of dust of irregular and filamentary structure given the likely merger history that we reasoned was needed to preferentially produce an FR-II. The unsettled dust in FR-IIIs is more likely to have been recently acquired given that dust settling time is estimated at $10^8 yr$ (van Dokkum & Franx 1995).

Natarajan & Pringle (1998) derived black hole re-alignment timescale for a case where an accreting black hole experiences a reverse torque due to the outer disk of the host galaxy. The re-alignment timescale is derived to be few $10^5 yr$ for an AGN radiating at a luminosity which is a tenth of the Eddington luminosity. If we use a more realistic estimate of the luminosity applicable to FR-I radio galaxies (0.001 or lower; Marchesini et al. (2004);

Ho (2009)) the black hole will realign over a time scale that is several orders of magnitude larger. Correspondingly the more powerful radio galaxies with their higher luminosities may tend to realign earlier (although still on timescales few orders of magnitude larger than $10^5 yr$). The observation that FR-Is have radio axes often aligned with the minor axes of their hosts suggests that they have been left relatively unperturbed for a long enough time to have their black holes realign with the minor axes. However, for the FR-IIIs, such undisturbed conditions may have eluded them and the black hole may have been prevented from realigning with the minor axis.

Dust-radio relationship appears to be stronger than dust-major axis relationship in FR-Is. In several FR-Is the radio axis continues to be orthogonal to the dust even when the dust is not located on the host major axis (see Section 3). We have already noted that FR-Is are more than adequately sustained with the fuel which is in sufficient supply in massive galaxies. The steady supply means that dust has had time to settle at the centre and form a stable disk on the major axis. The dust-radio relation gets established in these calm conditions. With dust-radio relation holding even when dust is not on the major axis (as seen in some FR-Is) it implies that any dust that comes in from outside and is at sufficiently close distance to the central region has a strong effect on the black hole angular momentum and can re-orient it.

At this stage we note that there are some remarkable similarities between the picture we are arriving at in understanding the dust properties of the two FR types and the scenario sketched by Baum et al. (1992) to explain the properties of the extended emission line regions. Already articulated clearly as "gradual, steady" feeding in the case of FR-Is and "impulsive" feeding in the case of FR-IIIs as inferred from the distinct extended emission line gas characteristics of the two classes, such a physical picture seems to also emerge from the dust properties. The association of large-extent emission line regions with their large rotational velocities (larger than the stellar rotational velocities) and the large kinematic excursions with FR-IIIs (whose hosts also exhibited morphological distortions) strongly suggested that the gas may have been acquired in recent mergers. In contrast the much smaller extents as well as lack of signif-

icant large scale motions in the emission line gas in galaxies that were almost all at cluster centres and hosting FR-Is suggested a local origin for the gas.

A potential upset for the model we have been developing for the FR-Is and FR-IIs is that the emission line gas rotation axis and the radio axis in FR-IIs align within about 30° (Baum et al. 1992). However as the authors themselves describe, the emission line gas nebulae in the FR-IIs, "show asymmetric rotation curves, large velocity excursions $\pm 100 \text{ km s}^{-1}$ from simple rotation, offsets of the kinematic and optical centers, broad lines, and misalignments of the rotation axis and the minor axis of gas distribution". It is indeed difficult to understand how in the midst of a merger and with the gas, "not yet settled into an equilibrium orbit or the activity generated in the galaxy nucleus has disrupted the orderly rotation of the gas" there is the tendency for alignment of the gas rotation axis and radio axis particularly when little alignment with the dust and radio axis is observed for FR-IIs (with dust and gas assumed to be present together).

The details of the process of fuel accumulation are not clear. At what stage in the fuel accumulation at the centre the activity is triggered is also not clear. However as low power FR-Is may need only a small amount of fuel to trigger them, they can also form in the early stages of ingestion of the externally generated fuel before the full accretion rate is reached or when generated in massive hosts (where there is a continuous supply of fuel which would have settled on the major axis) or in the late stages of an FR-II when the fuel is depleted but enough time has passed and the last vestiges of the dust has settled into a regular disk on the major axis. That the latter possibility cannot be the only way to form FR-Is was already ruled out by de Koff et al. (2000) since there is no difference in the dust masses estimated for large FR-IIs and small size FR-IIs, however it is still a possibility in some cases.

With FR-IIs being preferentially hosted by smaller ellipticals aided by mergers or larger ellipticals also aided by mergers (in the former because internally generated fuel is insufficient and then in the latter because the internal resistance requires higher accretion rates) and with lower mass ellipticals being more numerous given the Schechter

luminosity function, we have a situation where in samples of FR-IIs the dust will be seen preferentially on larger scales in a filamentary form rather than as disks at the centre.

What about the general lack of dust-radio perpendicularity in FR-IIs and the lack of relation between the radio axis and the host major axis in FR-IIs? With mergers aiding the hosts in producing jets powerful enough to overcome the ISM and produce FR-II structures this lack of perpendicularity relations may occur if the black hole spin is affected by the merger, whether by the triggered gas inflows or black hole-black hole merger (Hopkins et al. 2011). The likely long realignment timescales would ensure that the black hole axes (and hence the radio axes) show no relation with the incoming dust. We note that at the AGN scales there should be the expected perpendicularity between the accretion disk and radio jets but observations only pick out the larger-scale dust. The fueling is more dynamic in FR-IIs where the externally originating dust and gas could come in tranches of possibly differing orientations between them as also with respect to the major axis. The large-scale dust picked up in observations will therefore be of filamentary morphology and distributed with little correspondence with the radio axis. The same can be the case with high power FR-Is. These would be more likely generated in massive ellipticals that have had a merger that brings in more fuel than what the internally generated material brings.

At this stage we bring attention to the fact that in the several examples of restarted FR-II radio galaxies a change in axis between the two activity epochs is rarely observed. This can be taken to infer that the black hole spin axis remains steady between the two epochs. How can we understand this in the light of the reasoning for the observed lack of correlation of radio axes with either the dust or the host major axes in FR-IIs? It is clear that while mergers could have perturbed the black hole axes in FR-II hosts whatever is responsible for the interruption and re-triggering of the AGN, it has been gentler. It is possible for the black hole axis to remain steady within a merger event if we can associate the interruption and restarting of activity with the interruption to the fueling as each tranche of fuel is exhausted. Admittedly timescales are important here, for example

the timescale over which the dust (gas) segment gets depleted and the re-alignment timescale. In the context of timescales we point out that (based on the lack of relation between the dust and radio axes in FR-IIs) the AGN may be triggered even as much of the dust is settling and since there is no trailing radio emission seen, the entire AGN beam activity (including the quiescent phase and renewed activity) may be happening on a timescale small compared to the realignment timescale.

The "gradual, steady" feeding of the central engine in FR-Is with potentially limitless supply of fuel suggests that the fueling can remain active for a long time, perhaps much longer time than in FR-IIs. In these conditions it remains to understand how there can be any interruption to the activity in FR-Is.

There will be cases where the jets are oriented along the host minor axes. With less ISM to propagate through the powerful jets will advance more easily. These minor axis sources - as opposed to the major axis sources - will have a tendency to host a larger fraction of large size radio galaxies. In our earlier work (Saripalli & Subrahmanyam 2009) we reported such a tendency in the 3CR sample and we also reported the tendency for giant radio galaxies to have radio axes oriented along the host minor axes.

The richer environments of FR-Is may be environments that are conducive to creating edge-darkened structures because of the higher resistance that they offer the jets as they propagate out. However for FR-IIs, as we have already reasoned, a reliable means of generating them is via the lower mass ellipticals that have undergone mergers so low mass ellipticals that have had no merger history but reside in rich environments should have the least probability to host jets powerful enough to create FR-II structures. The more frequent mergers at higher redshifts means that there is a higher availability of cold gas and this is conducive to the formation of FR-IIs.

In the steady fuelling conditions inferred to be prevalent in most FR-I hosts the central engine may, in principle, never cease activity or at least may continue to remain active for a long time. However the multiple X-ray cavities observed in several galaxy clusters reveal a different picture that implicates multiple episodes of AGN activity

implying an unsteadiness of the AGN activity in these otherwise calm conditions. A missing factor is the feedback effect of the radio lobes which exercise control on cluster scales finally feeding back to the fueling itself (McNamara and Nulsen (2007) and references therein). With nearly every cooling flow cluster hosting multiple cavities the causes of AGN episodicity appear to be a feature of and linked to the specific conditions in a regulatory manner that can itself be a periodic phenomenon subject perhaps to disturbances to the large scale steady flows operating in the cluster.

7.2.2. *The classification based on optical spectra*

The traditional classification of radio sources based on their large-scale morphology is increasingly being examined in light of the central AGN spectroscopic properties. The radio morphologies may be viewed as consequences of the central AGN properties influenced or mediated by the prevailing conditions and state of the AGN (whether active, or waning or dead) and the environment through which the jet propagates.

As for the optical emission line characteristics of FR-Is and FR-IIs if all high ionization emission line radio galaxies are of FR-II morphologies, all FR-Is are low ionization emission line galaxies and some FR-IIs are low ionization emission line galaxies, then from the strong relation between the radio luminosity and the narrow-line luminosity it appears that the HEG FR-IIs are among the most powerful of the FR-II population (however also see Chiaberge et al. (2002); Buttiglione et al. (2010)). We will infer then that there is a high threshold jet power above which HEG characteristics manifest. This threshold power is higher than the dividing power at any optical host luminosity (to exclude FR-Is).

What then of the LEG FR-IIs? How do we understand a LEG FR-II? This was also the question raised and discussed by Laing et al. (1994) and Chiaberge et al. (2002). They gave several reasons to support the view that LEG FR-IIs are an isotropic population with at least a part being the parent population of BL-Lacs. With their close resemblance to FR-Is in their optical nuclear properties (Chiaberge et al. 2002) the FR-Is and LEG FR-IIs share a state of the AGN characterized by a weak central ionizing source (radiatively inefficient disk) and lack of any substantial gas or

dust torus. It is tempting to view this class of FR-IIIs as inclusive of sources that have waned in AGN activity or even FR-IIIs that have restarted at only small accretion rates. The mixed characteristics of FR-IIIs (HEG and LEG type) may be reflecting the variable central engine conditions. On the other hand the mixed radio morphologies observed in FR-Is has led to the speculation that at least some lobe-type FR-Is may be dying FR-II radio sources (Saripalli et al. 2012).

In (Chiaberge et al. 2000) a small number of FR-IIIs were reported clearly showing optical core properties indistinguishable from FR-Is. On examining the radio structures of the five FR-IIIs one is of FR-I morphology and three have characteristics that classify them closer to being relic sources: lobes with very low axial ratio and at least one of the lobes a relic lobe and weak hotspots. One other is a classic X-shaped source with bright hotspots in its main lobes. These five sources (one is an FR-I) are also reported to be in cluster environments. It is likely that the three FR-IIIs (2 are classified LEG-type and 1 HEG) with nuclear properties similar to FR-Is and radio morphologies that are more non-classic FR-II type are sources where the accretion rate has reduced to a level where it is not high enough to sustain an FR-II morphology and the radio morphology is showing the signatures of a dying FR-II.

On examining the morphologies of the FR-II radio galaxies in Buttiglione et al. (2010) although both classes of FR-IIIs (the LEG and HEG FR-IIIs) include a mix of source characteristics the LEG FR-IIIs are associated with a larger fraction of sources with restarted AGN (3C293, 3C236, 3C388) or relaxed double type (3C310, 3C401). In contrast the HEG FR-II mostly include sources with bright hotspot lobes and X-shaped radio sources (3C136.1, 3C223.1, 3C403). The LEG FR-II group does not include any with X-shaped morphology. If X-shaped structures are a result of deflection of backflows (Saripalli & Subrahmanyan 2009) it is not surprising that these sources are predominantly found to be associated with HEG FR-IIIs, sources that are characterized by bright hotspot lobes capable of generating strong backflows.

It is not necessary for all LEG FR-IIIs to also experience hot gas accretion for their sustenance like FR-Is. Given the different response times

of the sub-galactic narrow line regions and the several hundred kiloparsec-scale regions of synchrotron plasma it is possible that a current slowed-down state of the accretion can reveal an edge-brightened source on extended scales with an associated LEG AGN.

Besides having FR-I like AGN the LEG FR-IIIs share more properties with the FR-Is: they have circum-nuclear dust and show little evidence of ongoing starformation (Baldi & Capetti 2008). A compilation of these properties is needed for larger samples of LEG FR-IIIs to make stronger inferences.

The HEG FR-IIIs on the other hand nicely form an FR-II population that are the unbeamed counterparts of the broad-line radio galaxies and quasars (Chiaberge et al. 2002). The strong ionizing continuum and presence of gas and dust in these sources result in the strong narrow (low and high excitation) lines and broad lines where as the absence or only weak presence of a strong continuum and gas and dust in the FR-Is and LEG FR-IIIs prevents emission of strong narrow lines and high excitation lines. The absence of a broad line region in FR-Is has also been linked to the higher gas temperatures (Buttiglione et al. 2010) where dense gas clouds may not form.

We may point to the interesting issue of prevalence of FR-I quasars (Heywood et al. (2007) and reference therein). Having been identified as quasars the hosts must have high ionization as well as broad emission line spectra. This implies that the accretion rates are high and the disks are radiatively efficient. It is possible that (as also speculated by Heywood et al. (2007)) the resulting high power beams generated may be encountering high enough resistance in the form of dense gas that makes the powerful beams lossy (as in FR-Is) and not be subject to beaming effects nor create edge-brightened structures where they impinge on the ambient medium.

8. Summary

In the work presented here we have argued for a framework within which to understand the two basic morphological classes, the FR-I and FR-II type radio galaxies. We have made a connection between host galaxy properties and the FR classes that has crucially included observations of dust

and the relative orientations of dust, host major axis and radio axis. This contributes to a picture of FR classification that now encompasses a broader range of phenomena. With the backdrop of the Owen-Ledlow diagram we have attempted to connect various observations into a coherent picture for understanding the FR dichotomy.

Noting the quite different dust properties and relative orientations between dust, radio and major axes of the two FR-classes as well as differences in many other respects and also considering their relationship with the host galaxy (as displayed in the Owen-Ledlow diagram) we have tried to explore the physical conditions that could give rise to the seen differences. We are able to provide a qualitative framework for understanding the many characteristics of FR-I and FR-II radio galaxies by considering that although massive elliptical galaxies may generate sufficient fuel from internal sources to power the AGN given their high threshold jet energy flux they would more commonly host FR-I type source morphologies and also that for lower mass ellipticals on the other hand the lower threshold jet energy fluxes may more easily be breached and FR-II's more easily generated as a result of any additional external sources of fuel (coming in through mergers or interactions).

(a) The frequently seen alignments between dust, major axis and radio axis in FR-I's and their frequent association with more massive ellipticals suggest stable fueling conditions without need for mergers. The alignments suggest that they may have been left relatively unperturbed for a long enough time to have their black holes realign with the minor axes. However, for the FR-II's, such undisturbed conditions may have eluded them.

(b) Mergers appear crucial for the formation of FR-II's where as FR-I's form in more benign conditions.

(c) The observation of mostly aligned representations of multiple activity epochs in restarted radio galaxies suggests that while mergers could have perturbed black hole axes in FR-II hosts the cause for the interruption and re-triggering of the AGN is less perturbing and may not be due to a new merger event. The aligned structures demand that the black hole axis be steady within a merger event. A possible cause has been identified in the form of an association of the interruption and re-

triggering to the fueling as each tranche of fuel is exhausted. Moreover, the timescale for the entire beam activity (including the quiescent phase and renewed activity) is likely small compared to the realignment timescale.

(d) LEG FR-II's, a class that shares with the FR-I's a state of the AGN characterized by a weak central ionizing source may include sources that have waned in AGN activity. At least some LEG FR-II's are the transition FR-II's (whether dying or restarting). A bigger compilation of LEG FR-II's properties is needed to investigate their nature.

In the framework the association of an FR-type with an elliptical galaxy is flexible depending on the power of the jets that are created in the prevailing conditions, the type of environment they encounter as well as the age of the activity; mass and history of the host elliptical galaxy play a key role. A combination of host galaxy mass, its environment, the merger history, dust acquisition and distribution, accretion rates, ambient environment of the jets, black hole realignments may all need to be considered in understanding the FR-I and FR-II characteristics that we observe. We have tried to elucidate how these could influence the AGN and the radio source it generates.

Radio galaxies with powers at the extremes and hosted by ellipticals of a fixed absolute magnitude will be interesting to study to look at factors responsible for the different radio powers and morphologies.

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