FR0 Radio Galaxies and Their Place in the Radio Morphology Classification

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Abstract

So-called FR0 radio galaxies have recently emerged as a family of active galaxies with all the same properties as FRI radio galaxies except for their ratio of core to total emission, which is about 30 times higher than that of FRI sources. We show how their properties fit within the gap paradigm as low, prograde, spinning black holes whose progenitors are powerful FRII quasars that transitioned rapidly from the cold mode into advection-dominated accretion over a few million years. The prediction is that if sufficient fuel exists, FR0 radio galaxies will evolve into full-fledged FRI radio galaxies and the observational dearth of FRI radio galaxies compared to FR0s at low redshift tells us about the supply of gas in the low-redshift FR0s. Given the model prescription, this 5–1 FR0 to FRI ratio implies that at low redshift, the FRII quasar class of active galaxies struggles to fuel its black hole beyond 1.3 times its original mass. In addition to this, we illustrate model prescriptions for the black hole mass, black hole spin, redshift, and environment distribution for FR0 radio galaxies by fitting them within a paradigm that views them as a continuous class of active galaxies that are sandwiched between FRII quasars and FRI radio galaxies.

Key words: galaxies: active – galaxies: jets – quasars: supermassive black holes

1. Introduction

Although selection effects singling out active galactic nuclei (AGNs) with powerful jets are responsible for our current classification scheme into FRI and FRII jets (Fanaroff & Riley 1974), deep large area surveys have revealed that compact (or small-scale) jets constitute the dominant population at least at low redshift (Baldi & Capetti 2009, 2010; Sadler et al. 2014). These FR0 radio galaxies appear difficult to distinguish from the FRII and FRI low-excitation radio galaxies (LERGs; Capetti et al. 2017a, 2017b) but on closer inspection their line, X-ray luminosities, and core properties show them to be environmentally indistinguishable from FRIs (Baldi et al. 2015; Torresi et al. 2018). Because there are significantly less FRI radio galaxies than there are FR0 radio galaxies, Baldi et al. (2019) concluded that FR0s cannot be thought of as young FRIs. In this work, however, we circumvent the criticism against FR0s evolving into FRIs by recognizing that FR0 radio galaxies need not be young objects, but accreting, middle-aged black holes, having evolved for hundreds of millions of years or more. As a result of their lack of youth, an evolutionary connection to extended jet emission as an FRI radio galaxy is plausible but not inevitable, as there must be a sufficient amount of fuel to evolve the FR0 into its future FRI state. The observational discrepancy between the number of FRIs compared to the number of FR0s is then interpreted as the result of a limit on the fuel of FR0s in the low-redshift universe. We will show that the giant black holes in the low-redshift FRI radio galaxies fit into a paradigm in which they have accreted enough matter into their nuclei to become at least 30% more massive than they were when they formed. In addition to this, we predict black hole masses and spins, as well as the redshift and environment distributions for FR0s.

Our paper is organized as follows. In Section 2 we illustrate how the model accommodates FR0s. In Section 3 we explore their environments. In Section 4 we connect them to their immediate ancestor, WLRG/FRIIs. In Section 5 we explore their black hole masses and redshifts. In Section 6 we conclude.

2. The Model

The gap paradigm for black hole accretion and jet formation is a phenomenological scale-invariant framework for understanding black hole feeding and feedback that provides insight into observations across the mass scale. The model has been applied to the most basic questions in AGNs, such as the radio-loud/radio-quiet dichotomy and the jet–disk connection by opening a window into powerful jet production from retrograde accreting black holes (Garofalo et al. 2010); the redshift distribution of jetted AGNs and compatibility with the Soltan argument by recognizing a natural time evolution toward prograde spinning black holes (Garofalo et al. 2016); the nature of the fundamental plane (Garofalo et al. 2014); the redshift distribution of BL Lac objects and flat spectrum radio quasars (Garofalo et al. 2019) and the environment dependence of radio galaxies, as well as jet power/lifetime correlations (Garofalo et al. 2019), among others. Despite the existence of simple cartoons that can describe the FR time evolution, a surprising degree of quantitative predictability exists that in this work we will apply to FR0 radio galaxies. We outline the essential features of the model using Figures 1–3. Figure 1 is the result of the numerical solution of the force-free equations for jet power as a function of black hole spin, with retrograde orientations of the disk captured by the minus sign and prograde orientations of the disk captured with positive signs. With this figure we can identify regions of the spin space that correspond to relatively weaker jets, and will be identified with the FR0 radio galaxies. Figure 2 is new, introduced to describe, with better time resolution, the evolution of the most powerful FRII quasars in a way that is directly connected to the standard figures that have been used to apply the model. Figure 3 is less well resolved in time but illustrates a more general application of the model, with a focus on the variety of different paths for FRII quasars. In practical terms we should think of Figure 2 as being included in Figure 3, as Figure 2 is a more detailed version of Figure 3(c), the lowest series of panels in Figure 3, which describe the predicted time evolution of the most...
massive and therefore most powerful FRII quasars that are born in gas-rich mergers. For the small fraction of post-mergers that allow stable retrograde accretion, the lowest panel in Figure 3(c) shows a powerful FRII jet emerging from a black hole accreting in a cold mode, surrounded therefore by a thin, radiatively efficient, accretion disk. As a direct consequence of the powerful jet feedback, the accretion disk transitions relatively rapidly into an advection-dominated system (ADAF) on a timescale of about a few million years (see applications of this evolution in Garofalo et al. 2019). Hence, the second panel in Figure 2 shows an ADAF accreting black hole that has not yet been fully spun down so it remains in retrograde mode. This is equivalent to what is shown in Figure 3(c). The continued accretion will spin such black holes down on timescales of hundreds of millions of years, making them transition toward a state characterized by low luminosity and a disappearing jet as the black hole spin approaches zero value. Such objects have been identified as the WLRG/FRIIs of Tadhunter et al. (2012). For the purposes of this work, however, our interest is in the evolution toward a renewed jet state as the system evolves into the prograde spin regime. For a fixed magnetic field threading the inner disk $B_d$, the jet power in the prograde regime increases as the spin increases from zero spin and tends to level off in the intermediate prograde regime (see Equation (1) and Figure 1). This comes about in the numerical solution as a result of the existence of the zero flux boundary condition in the gap region inside of the innermost stable circular orbit (i.e., the Reynolds condition). As the spin increases in the prograde direction, the Blandford–Payne jet is weaker, while the Blandford–Znajek jet is stronger. As a result they tend to balance out and this produces a jet power versus spin that is less steep in the prograde regime compared to the retrograde one. At low prograde values, the jet is weaker but it increases from zero spin and we identify a region of the jet power versus spin space that can model compact/weak FR0 radio galaxy jets. For simplicity, we choose 0.1 as the value of the dimensionless black hole spin to model FR0s. Near this relatively low value of spin the jet is not negligible yet not powerful enough to constitute an FRI LERG. Unlike Figure 3(c), which shows the state of the system at a high prograde spin, our focus here is on the state of the system at low prograde spin, in a region of the parameter space where weak, compact jets, might be prescribed. Hence, we focus on the a $\sim$0.1 region and produce a panel prescribing a weak jet emerging from the black hole (Figure 2, third panel from bottom). In short, Figure 2 is nothing more than Figure 3(c) with an additional panel introduced between the retrograde
panels and the high-spin prograde panel:

\[ L_{\text{jet}} = 5 \times 10^{47} \text{ erg s}^{-1} f(a)(B_d / 10^5 \text{ G})^2 m_\odot^2. \]  

(1)

Equation (1) (from Garofalo et al. 2010) constitutes the jet power in terms of a function of spin \( f(a) \) capturing the effects of the gap region on the magnetic flux, the magnetic field in the inner disk region, \( B_d \), and the black hole mass in terms of 1 billion solar masses, \( m_\odot \). In the next section we will further explore the implications of FR0s fitting into the paradigm as low-spinning, prograde accreting black holes.

3. FR0 Radio Galaxies

As a result of the small value of the black hole spin, the jet is not powerful, and like Baldi et al. (2015), who identified the possibility that FR0s could be low-spinning black hole objects, we classified systems for which the spin is near the dimensionless value of 0.1 as belonging to the FR0 classification.

Continued accretion will eventually turn the FR0 LERG into an FRI LERG, as can be seen in Figure 2. This can only occur, however, if sufficient fuel is available for the system to build its black hole mass by the amount needed to spin it up to about 0.2 or beyond. A thin disk accumulates mass onto the black hole as determined by integrating the mass needed to shift the inner edge of the disk \( r_{\text{in}} \) from the innermost stable circular orbit associated with the original high retrograde value to the final prograde value via Equation (2) (Raine & Thomas 2005; Kim et al. 2016):

\[ M_{\text{acc}} = \int dm / (1 - 2 m / 3 r_{\text{in}})^{1/2}. \]  

(2)

The expression is written in units such that Newton’s gravitational constant, as well as the speed of light, are equal to 1. \( M_{\text{acc}} \) is the mass that is accreted onto the black hole, \( m \) is the black hole mass, and \( r_{\text{in}} \), as mentioned, represents the inner edge of the disk. If we follow the panels of Figure 2, this means \( r_{\text{in}} \) evolves from about 8.7 gravitational radii (0.9 spin) to about 5.3 gravitational radii (0.2 spin). Therefore, in order for the dying FRII LERG jet to re-emerge as an FRI LERG jet, the black hole must accumulate a mass of about 1.3 times its original mass. This can be seen in Figure 4, where the increase in black hole mass is shown as the black hole spins down and then up in the prograde regime. For the most massive systems of interest to us, the original black hole may be in the \( 10^8 \)–\( 10^9 \) solar mass range, which means a minimum amount of mass in the range of \( (0.03-0.3) \times 10^9 \) solar masses must be accreted. The observational fact that at low redshift the number of FRI radio galaxies is only about one-fifth the total number of FR0 radio galaxies, constitutes a constraint and enables the prediction of the amount of material that is available to be accreted onto the black hole at low redshift in the environments of these low-redshift FR0 radio galaxies. Unlike in Baldi et al. (2019), however, it is important to recognize that we are indeed postulating an evolution from FR0s into FRIs, the difference being that, in our framework, it is reasonable that FR0s are not young objects but the product of prolonged accretion-spinning.
timescales that easily accommodate hundreds of millions if not billions of years. Given the amount of fuel that must be supplied to the black hole for an FR0 to transition to an FRI, however, we argue that it may be reasonable to imagine that not many low-redshift systems funnel enough fuel into their black hole sphere of influence to ultimately succeed. Hence, we do not expect all FR0 objects to continue generating offspring FRI LERGs. Of course, these ideas can be subjected to observational scrutiny.

4. FR0 Environments

Recent work has demonstrated the connection between the distribution of dark matter halos in clusters versus field environments and the radio quasars and galaxies modeled in the gap paradigm (Garofalo et al. 2019). In this section we apply those ideas to predict FR0s to be dominant in clusters as opposed to isolated fields. To appreciate this, we invoke Figure 3 from Garofalo et al. (2019), showing the time evolution and environments of radio quasars formed in mergers around black holes of different masses. In Figure 3(a) we have the smallest black holes whose jets are therefore relatively weaker, which makes them ineffective in altering the mode of accretion. Such black holes remain radiatively efficient and therefore rapidly spin down and then up in the prograde direction. Because these accreting black holes are the smallest, they tend to be formed in isolated field galaxies whose dark matter halos are smaller. In Figure 3(b) we see the time evolution of black holes with intermediate black hole masses. Such objects produce more effective jet feedback than in Figure 3(a) and therefore eventually experience a change in their accretion state from radiatively efficient to ADAF. These objects can be found both in the field as well as in clusters. In Figure 3(c), instead, we see the evolution of the most massive black holes. Such objects produce the most powerful and effective jet feedback heating their environment, which...
The continuous accretion picture adopted here to model the FR0s requires that their black holes possess intermediate masses in the hierarchy of radio galaxies among the most massive black holes. On average, i.e., among the most massive black holes, FRII quasars or FRII HERGs have the lowest black hole masses, while the FR0 radio galaxies and FRI LERGs have increasingly larger black hole masses on average. We have been precise about this in that continuous accretion provides the black hole with about an additional 30% of its original mass for it to become a low, prograde, spinning black hole with sufficient spin to enter the FRI LERG classification. The model therefore prescribes FR0 LERG black hole masses to be on average no larger than about 30% more massive than the average FRII HERG. For the fraction of FR0 LERGs that have enough fuel to spin their black holes up into the higher prograde regime to become FRI LERGs, such objects will possess the largest black holes. Hence, in terms of their black hole masses, FR0 LERGs are sandwiched between FRII HERGs and FRI LERGs. This is confirmed in studies on FRICAT and FR0CAT. In addition to a quantitative prescription for their black hole masses, the model allows us to also prescribe the redshift dependence of the various classes of FRI galaxies described in this work. Restricting our focus on the most massive black hole accreting radio galaxies, the ones captured in Figures 3(c) and 2, the transition to ADAF/LERG states slows the evolution timescales down by at least two orders of magnitude compared to the objects described in Figure 3(a). Hence, there is a non-negligible redshift gap between the FRII HERGs of Figures 3(c) and 2, and the FR0 LERGs of Figure 2, and an even greater redshift gap between the FRII HERGs and the high-prograde-spin FRI LERGs of Figures 3(c) and 2. For a recent application of the quantitative nature of that redshift gap between the FR radio galaxy subclass of AGNs, as applied to flat spectrum radio quasars and BL LACs, see Garofalo et al. (2019).

5. Progenitor WLRG/FRIIs

By following the evolution of powerful FRII quasars or FRII HERGs in the paradigm via Figure 3(c), we note that the progenitors to the FR0 radio galaxies in terms of jets must be objects that were low-spinning retrograde black holes accreting in advection-dominated form. These objects were modeled in Garofalo et al. (2019) as the WLRG/FRII systems explored in Tadhunter et al. (2012). FR0 radio galaxies are therefore to the flipside of the low, retrograde spin objects and therefore are low-spinning, prograde, accreting black holes accreting in ADAF form. Because there is an evolutionary link between these two subclasses of the radio galaxy population in the model, we expect a greater number of objects that fit within the WLRG/FRII classification compared to the FR0 radio galaxy group. Again, this is a product of the possibility that the amount of fuel available to be accreted onto the black hole may terminate prior to reaching low prograde spin values. Of course, on average, the redshifts for the WLRG/FRI are larger than those for the FR0 radio galaxies, which produces different observational challenges for the two subpopulations of radio AGNs. In other words, the detection threshold introduces a bias in favor of the FR0s compared to the WLRG/FRIIs, which appears to be compatible with the observations in Capetti et al. (2017b) and Baldi et al. (2018) of the FRICAT and FR0CAT samples.

6. Black Hole Mass and Redshift

The continuous accretion picture adopted here to model the FR0s requires that their black holes possess intermediate masses in the hierarchy of radio galaxies among the most massive black holes. On average, i.e., among the most massive black holes, FRII quasars or FRII HERGs have the lowest black hole masses, while the FR0 radio galaxies and FRI LERGs have increasingly larger black hole masses on average. We have been precise about this in that continuous accretion provides the black hole with about an additional 30% of its original mass for it to become a low, prograde, spinning black hole with sufficient spin to enter the FRI LERG classification. The model therefore prescribes FR0 LERG black hole masses to be on average no larger than about 30% more massive than the average FRII HERG. For the fraction of FR0 LERGs that have enough fuel to spin their black holes up into the higher prograde regime to become FRI LERGs, such objects will possess the largest black holes. Hence, in terms of their black hole masses, FR0 LERGs are sandwiched between FRII HERGs and FRI LERGs. This is confirmed in studies on FRICAT and FR0CAT. In addition to a quantitative prescription for their black hole masses, the model allows us to also prescribe the redshift dependence of the various classes of FRI galaxies described in this work. Restricting our focus on the most massive black hole accreting radio galaxies, the ones captured in Figures 3(c) and 2, the transition to ADAF/LERG states slows the evolution timescales down by at least two orders of magnitude compared to the objects described in Figure 3(a). Hence, there is a non-negligible redshift gap between the FRII HERGs of Figures 3(c) and 2, and the FR0 LERGs of Figure 2, and an even greater redshift gap between the FRII HERGs and the high-prograde-spin FRI LERGs of Figures 3(c) and 2. For a recent application of the quantitative nature of that redshift gap between the FR radio galaxy subclass of AGNs, as applied to flat spectrum radio quasars and BL LACs, see Garofalo et al. (2019).

7. Conclusions

This paper applies the gap paradigm for black hole accretion and jet formation to the emerging class of FR0 radio galaxies. These objects live in environments that are analogous to those of FRI radio galaxies in all respects, but differ from them in their ratio of core to extended emission, which is tens of times larger. Using the framework of low, prograde, spinning black holes surrounded by advection-dominated accretion flows, we have argued that they are not young objects but the result of renewed jet activity following the evolution of a black hole whose past involved a retrograde spin-down phase. As a result of their advection-dominated accretion disks, such objects struggle to spin their black holes up, and therefore require hundreds of millions of years, if not billions of years, to reach spin values for which the paradigm prescribes non-negligible jets. Incidentally, this timescale is responsible for the appearance of powerful jets at sufficiently separated cosmic times (Garofalo et al. 2019). FR0 radio galaxies are thus imagined to be middle-aged, such that if sufficient fuel allows them to be spun up further in the prograde direction, they will evolve into more powerful jet producers, FRI radio galaxies, as they get older. We have shown that the compatibility between the model and observations requires that most low-redshift FR0 radio...
galaxies not have the ability to accrete beyond about 30% of their original black hole mass, a quandary that can be explored observationally. We have also shown that because FR0 radio galaxies were born as the FRII quasars with the most massive black holes, this particular family of radio galaxy prefers rich cluster environments over isolated field galaxies, and possesses intermediate values of black hole mass among the most massive class and intermediate redshift values. To conclude, we point out that FR0s do not fit into the paradigm as radio-quiet quasars/AGNs—as the weakness or compactness of their jets might suggest—because their environments are not compatible with those for radio-quiet quasars/AGNs, as seen in the top two panels of Figure 3(a).

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