FRI radio galaxies at 1 < z < 2

Studying the building blocks of today's most massive galaxies and clusters by finding low luminosity radio galaxies at high-z

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Abstract

Low luminosity “FRI” radio galaxies constitute by far the largest population of radio loud AGN in the local universe. They are invariably associated with the most massive elliptical galaxies, they are likely to possess supermassive black holes of 10^8 solar masses and higher and, differently for the more powerful “FRIIs”, they reside in rich clusters of galaxies. Therefore, they can be used as “beacons” to find high-z clusters and giant elliptical galaxies and study their formation and evolution. However, because of the tight luminosity-redshift dependence of flux limited samples, very few of those objects are known in the distant universe. We have recently selected a sample of 37 candidate low luminosity (FRI) radio galaxies at 1 < z < 2 in the COSMOS field using a multiwavelength selection technique. Larger samples can be selected in the future by applying similar criteria to surveys covering large sky areas. Our work opens the way for discovering and investigating galaxies and clusters associated with faint radio galaxies in the redshift range where traditional searching techniques (X-ray, optical/nearIR imaging) have struggled to yield solid cluster candidates to date. This clearly constitutes a pilot study for objects to be observed with future high-resolution and high-sensitivity instruments such as the EVLA and ALMA in the radio band, HST/WFC3 and 30m-class ground based telescopes in the optical and near-IR, JWST, as well as next generation X-ray satellites.

1. Overview

Amongst the most energetic phenomena in the universe, radio galaxies are excellent laboratories in which we investigate some of the major challenges of today's astrophysics, such as accretion onto supermassive black holes (SMBH), the associated formation of relativistic jets (e.g. Blandford 1990, Livio 1999), the feedback processes of an ``active'' SMBH in the star formation history of a galaxy (e.g. Hopkins et al 2006) and the role of the AGN in injecting energy in the intracluster medium (Fabian et al. 2006). The original classification of radio galaxies is based on their radio morphology: ``edge-darkened'' (FR Is) are those in which the surface brightness decreases from the core to the edges of the source, and typically display large lobes or plumes; ``edge-brightened'' (FR IIs), are those in which the peaks of the brightness is located near the edges of the radio source. FR I galaxies typically have a radio power lower than that of FRII sources, with the FR I/FR II break set at $L_{178MHz} \sim 2 \times 10^{33}$ erg s^{-1} Hz^{-1} (Fanaroff & Riley 1974). However, the transition is rather smooth and both radio morphologies are present in the population of sources around the break. The FR I/FR II break (at low redshifts) also depends on the luminosity of the host galaxy, as shown by Owen & Ledlow (1994). From the optical point of view, FR Is are invariably associated with the most massive galaxies in the local universe (e.g Zirbel 1996, Donzelli 2007), thus they are also most likely to be linked with the most massive black holes in the local universe. Furthermore, FR Is are usually located at the center of rich clusters. On the other hand, at low redshifts, FR IIs are generally found in regions of lower density, while only a few FR II are found in richer groups or clusters at redshifts higher than ~0.5 (Zirbel 1997).

Finding high-z FR Is and understanding their evolution will help us to address a number of other unsolved problems in current astrophysics, such as studying the properties of the "building blocks" of massive elliptical galaxies present in today's universe, assessing the relationship between giant elliptical and their central supermassive black holes, and studying the formation and evolution of galaxy clusters.

However, flux-limited samples of radio galaxies such as the 3CR and its deeper successors 6C and 7C catalogs are limited by the tight redshift-luminosity correlation, i.e. the well known Malmquist bias. This, along with the steep luminosity function of these objects, gives rise to a selection bias resulting in detection of high luminosity sources only at high redshifts and low power sources exclusively at low redshift. It is therefore unsurprising that, in the above mentioned catalogs, all "high z" objects are FR II sources (or QSOs), while FR Is are only found at $z < 0.2$.

In Chiaberge et al. (2009) we selected a sample of 37 "candidate" low power radio galaxies (FRI) at high-z, taking advantage of the exceptional multiwavelength dataset collected as part of the COSMOS survey (Scoville et al. 2007). In absence of spectroscopic redshift measurements, the selection method is based on multiple steps which make use of both radio and optical constraints. The basic assumptions are that 1) the break in radio power between low-power FR Is and the more powerful FR IIs does not significantly change with redshift, and 2) that the photometric properties of the host galaxies of low power radio galaxies in the distant universe are similar to those of FR IIs in the same redshift bin, as is the case for nearby radio galaxies. See Chiaberge et al. (2009) for details.

In Fig. 1 we show a few examples of these high-z galaxies: for each object, the left panel shows the VLA image at 1.4MHz, while the right panel shows the 1-orbit HST/ACS I-band image (Koekemoer et al. 2007). The optical magnitude of the optical counterparts is around V=24 (Vega mag) or higher. As soon as the redshifts of all sources will be spectroscopically confirmed, this will constitute the first sample of FR Is discovered in the range of redshift between 1 and 2. As of February 2009, only 3 spectroscopic redshifts are available for our targets: two of them were collected as part of the z-COSMOS project, and one (for the brightest galaxy in our sample, K=17.6 Vega mag) has been measured by our group using the 3.5m Italian Galileo Telescope. All of the three redshifts are close to their photometric value, and confirm that our selection criteria identifies objects in the correct redshift range. Such a work is a pilot-project for future studies, and the same selection criteria could in principle be applied to other fields and may lead to discovering a large number of such objects. In the following sections we outline the potential outcomes of studying low luminosity radio galaxies in the distant universe for some important unsolved questions in astrophysics.

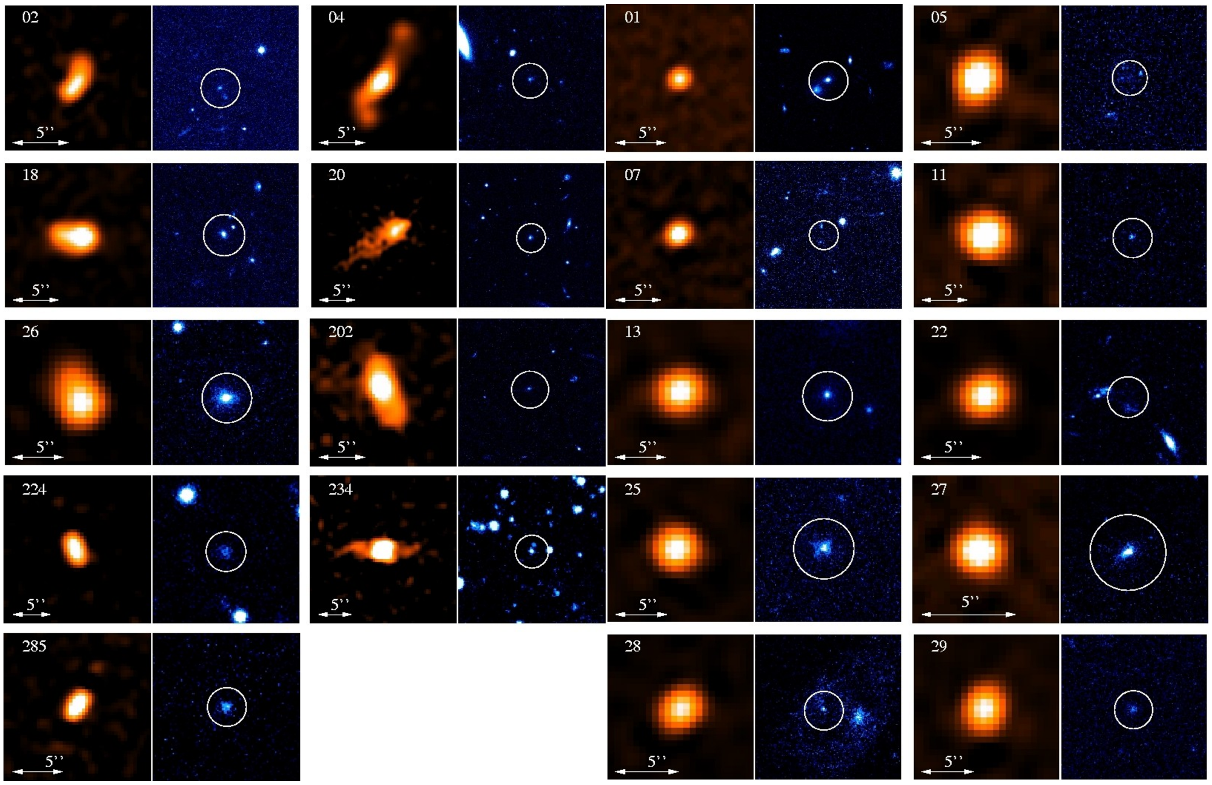

Figure 1: *High-z low luminosity radio galaxies in the COSMOS field from the sample of Chiaberge et al. 2009*

2. The importance of high redshift FRIs for understanding the formation of clusters and elliptical galaxies

In the local universe, ~70% of the entire population of FR Is is associated with cD-like galaxies (Zirbel 1996), and almost all low-z FR Is reside in clusters of various richness (Zirbel 1997). Finding high-z FR I with properties similar to those found in the local universe can be a breakthrough for studies of the evolution of galaxies and clusters. Using radio galaxies as beacons of high-z clusters is not a new idea. In the recent past, high-z radio galaxies have often been used to find protoclusters and massive galaxies at the epoch of their formation (e.g. Pentericci et al. 2001; Zirm et al. 2005; Miley & De Breuck 2008). However, all the above studies used high power sources with extremely high redshifts ($z > 2$). These are rare objects in the universe whose connection to today's radio galaxies is not clear. It is also unclear whether their protocluster environment has virialized by that epoch, since it is difficult to detect the X-ray emission of the ICM. Powerful FR IIs have the disadvantage of having strong emission from the nucleus and powerful relativistic plasma jets, which may strongly influence the properties of the host galaxy and may hamper studies of the environment, in particular in the X-ray band (e.g Fabian et al. 2003). FR Is are less powerful AGNs, they are more similar to “normal” inactive galaxies than FR IIs, and allow us an easier investigation of the surrounding environment, with dramatic impact on cosmological studies. FR Is with distorted morphologies were also used to search for clusters, but only out to a redshift $z < 1$ (Blanton et al. 2000). To date, only a handful (less than 10) X-ray confirmed clusters are known at $z > 1$, and none of them is at a redshift higher than 1.45 (see Rosati et al. 2002, for a review). Studying high-z low luminosity radio galaxies might be a very efficient way of finding a large number of clusters in such a crucial redshift range. The clusters associated with FRI radio galaxies at $1 < z < 2$ might in fact represent the "missing link" between the extended Hα and Lyα emitters discovered around powerful radio galaxies at $z > 2$ (e.g. Kurk et al. 2004) and the well formed clusters of galaxies at $z < 1$.

As part of our pilot project (Chiaberge et al. 2009), we searched for clusters of galaxies around our high-z FRI candidates using the data from the COSMOS survey to find extremely red objects around our FR I candidates. Although there is still some level of degeneracy between objects that are intrinsically red and redshifted objects, this method seems to lead to promising results, even at the qualitative level achieved in pilot study. In Fig. 3 we show nine cluster candidates found with the latter method. We produced RGB "color" images using Spitzer Space Telescope data at 3.6μm for the R channel, z-band for the G channel, and v-band for the B channel.

In order to achieve more detailed information about the morphology, radial brightness profile and photometric properties of the host galaxies, their possible interaction with immediate neighbors, the properties of the cluster environment, and to derive the color-magnitude relation for early-type cluster galaxies, deep high-resolution optical and near-IR images and possibly slitless spectroscopy should be obtained as soon as the WFC3 is installed on HST. Spectroscopy studies with 30m-class telescopes will allow us to measure the redshift of a significant number of cluster members and to obtain the stellar velocity dispersion σ for cluster elliptical galaxies. Since the hosts of FR Is are in all aspects "normal" early-type galaxies, this will enable us to constrain the evolution of the fundamental plane (FP) up to an unprecedented redshift (the current limit is set by only one galaxy at z=1.27, van Dokkum & Stanford 2003). Furthermore, the future generation of high-sensitivity X-ray telescopes (e.g. IXO) will allow us to study in detail the properties of the ICM around our sources.

These studies represent a crucial step to unveil the formation processes of baryonic matter and strongly constrain both the epoch of metal enrichment and the formation age of stars in cluster ellipticals, with fundamental bearings on cosmological models.

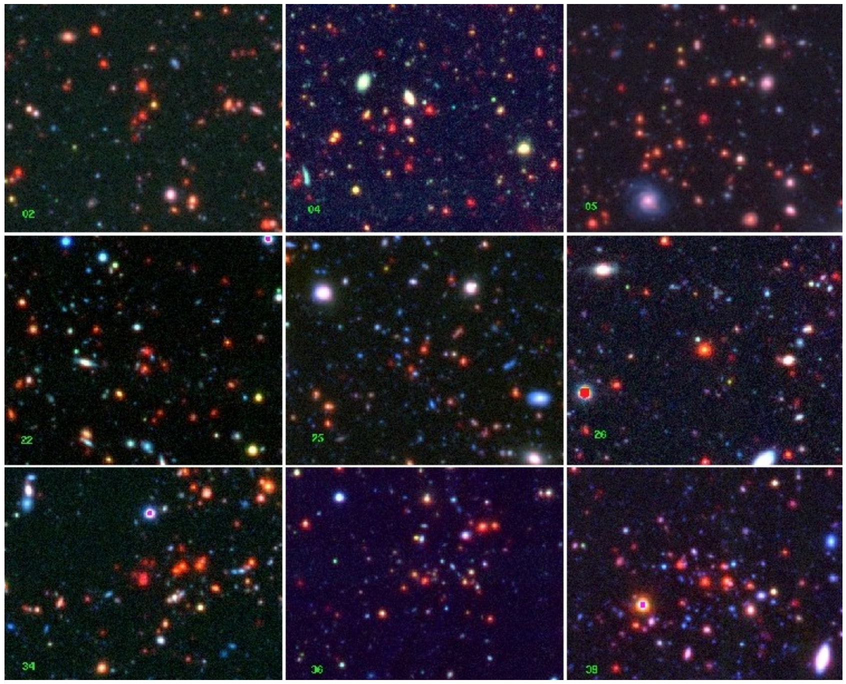

Figure 2 *RGB images of nine cluster candidates found around our high-z FR I candidates. The "color" images are obtained using Spitzer data at 3.6μm for the R channel, z-band for the G channel, and V-band for the B channel. The projected scale of each image is ~110" x 90". The photometric redshifts of the candidates are between 1.30 and 2.04.*

3. High-z FR I radio galaxies: discovering the progenitors of the local population

Typically, FR I are characterized by jets that are relativistic only up to the scales of ~1kpc, although their radio structure may extend up to the Mpc scales. FR IIs normally show strong emission lines of both high and low excitation, while FR Is usually have very faint or low excitation emission lines, or no emission lines at all. In the 3C catalog (the most extensively studied catalog of radio sources) FR Is are found at $z < 0.2$, while in its deeper successors 6C and 7C a few FR Is have been found up to $z \sim 0.7$. Before our work (Chiaberge et al. 2009) no FRI radio galaxies were known to exist at $z>1$, besides one candidate discussed in Snellen & Best (2001) at $z = 1.0$. Nevertheless, there is evidence that the space density of radio-loud AGN substantially increases with redshift up to $z \sim 2.5$. And interestingly, recent work by Sadler et al. (2007) find that in the redshift range $0 < z < 0.7$ low power radio galaxies undergo significant evolution. Thus, they might be significantly more abundant at $z > 1$ than in the local universe.

What are the properties of FR Is at $z > 1$? What is the structure of their host galaxy? How is it related to the supermassive black hole, which we know is already well formed because of its "active" status? Do high-z FR Is evolve into local FR Is or into FR IIs?

The VLA/COSMOS radio maps show that 28 out of the 37 sources in our sample of high-z FRI candidates are only slightly resolved or unresolved. Only 9 objects show a radio structure on the scales of a few tens of kpc. This appears to be at odds with the properties of FRIs in the local universe. Although it is likely that the non-detection of large-scale structures results from the high frequency at which the COSMOS observations are performed, it is also possible that our high-z FR I candidates are intrinsically small. In fact, even the higher power FR IIs in this redshift range appear smaller than their lower redshift counterparts (e.g. Kapahi 1985, Gopal-Krishna & Wiita 1987). It is therefore possible that our candidates are just the progenitors of the FRIs we observe in the local universe. The use of the EVLA and ALMA will be necessary in order to achieve sufficient signal to noise ratio and spatial resolution to study these faint and distant objects in more details in the radio band.

4. Accretion and ejection processes and implications for the AGN unification

What are the physical conditions of matter accreting onto the central supermassive black hole? At low redshifts, FRIs are considered as "starved quasars", as their faint nuclear radiation is dominated by non-thermal emission from the base of the relativistic jet (Chiaberge et al. 1999), and accretion onto their central black hole possibly occurs with a very low radiative efficiency, possibly in the form of an ADAF (advection dominated accretion flow, see e.g. Falcke et al. 1995, Baum et al. 1995, Allen et al. 2006). Besides their "low" radiative power, SMBHs in FRIs are imponent energy sources, which can produce relativistic jets, heat the surrounding gas and possibly quench further star formation. Jets and "bubbles" blown by FR Is are thought to be responsible for creating the "holes" and the shocks observed in the central regions of clusters (e.g. Fabian et al 2003, 2005).

The picture we obtain from low-z studies is that FRI jets appear to be almost invariably associated to low-radiative efficiency accretion. However, a few FR Is showing a quasar-like spectrum are present, even at low redshifts (e.g. 3C 120, e.g. Ballantyne et al. 2004). But there are hints that such FR I-quasar "exceptions" may become more common at higher redshifts, or even become prevalent (Heywood at al. 2007). If that is the case, it would indicate a profound change with redshift of the physical properties of FR Is with important consequence on our knowledge of the accretion onto SMBH and jet production.

However, in our sample of FRIs at $1 < z < 2$, only one object shows a point-like morphology in the HST/COSMOS images, while the fraction of FRII-QSOs in the same range of redshifts is ~40% (e.g. Willott et al. 2000). A possible scenario is that the smaller fraction of FR I-QSO as compared to the fraction of FR II-QSO simply results from the dependence of such fraction on luminosity (Willott et al. 2000). This may reflect a reduction of the opening angle of the "obscuring torus" as luminosity decreases (the so called "receding-torus" model). Alternatively, most high-z FR Is may intrinsically lack significant broad emission line region and thermal disk emission as is for the FR Is in low-z samples (e.g. Chiaberge et al. 1999). These issues are perfectly suitable to be explored with deep imaging to determine the nature of the hosts using HST/WFC3 and JWST in the IR, coupled with spectroscopy using an 8m-class telescope or higher to determine the presence or absence of any strong broad emission lines.

Conclusions

The search for high-z FR I candidates we presented in Chiaberge et al (2009) constitutes a pilot study for objects to observed with high-resolution and high-sensitivity future instruments. The EVLA and ALMA will provide us with crucial information on the radio morphology and age of the radio sources, they will help us to understand whether or not the objects we discovered are intrinsically small, and if they are "progenitors" of the local FR I population. When WFC3 is installed on the HST, it will be possible to study in greater details the properties of the host galaxies and the cluster environment in the optical and IR, with important bearings for our knowledge of the origin of the most massive galaxies and galaxy clusters. Clearly, these studies will be complemented and further expanded when 30m-class telescopes and JWST will be available. Among others, deep near-IR spectroscopy will allow us to measure the stellar velocity dispersion of massive elliptical hosts of the newly discovered low luminosity radio galaxies possibly in their final stages of formation. Deep optical spectroscopy will allow us to measure redshifts and spectral properties of cluster galaxies and constrain the fundamental plane of elliptical galaxies out to unprecedented redshifts. The future generation high-sensitivity X-ray satellites (e.g. IXO) will allow us to investigate the ICM and constrain models of cluster formation with important bearings on cosmological studies.

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