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Study of Spectral Energy Distributions of low-luminosity radio galaxies at z ∼ 1–3: a high-z view of the host/AGN connection

Ranieri D. Baldi[1], Marco Chiaberge[2] and Alessandro Capetti[3]

[1]SISSA, via Bonomea 265, 34136 Trieste, Italy
email: rbaldi@sissa.it

[2]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

[3]INAF-Osservatorio Astronomico di Torino, Strada Osservatorio 20, 10025 Pino Torinese, Italy

Abstract. Low-luminosity radio galaxies, common in the local Universe, are associated with giant elliptical galaxies and typically with a FR I radio morphology. However, they are rare in flux-limited samples of distant radio-loud (RL) AGN due to a selection bias. Chiaberge *et al.* (2009) selected the first sizeable sample of FRI candidates at 1<z<3, in the COSMOS field. We study the Spectral Energy Distributions (SEDs) of this low radio power sample from the far-UV to the Mid-IR wavelengths. Our results show that the hosts of these high-z low-luminosity radio sources are old massive galaxies, similar to the local FR Is. However, for half of the sample the UV and MIR excesses indicate the possible significant contribution from star formation and/or nuclear activity, not seen in low-z FR Is. Our sources display a wide variety of properties: from possible quasars at the highest luminosities, to low-luminosity old galaxies.

Keywords. Galaxies: active – galaxies: high-redshift – Galaxies: nuclei – Galaxies: photometry

1. Introduction

In the local Universe, our acknowledgment about the RL AGN population is well based on large number of observations and studies. Radio galaxies can be classified based on their radio morphologies into: 'edge-darkened' (FR I) and 'edge-brightened' (FR II) sources. Such a classification also reflects a separation in radio power at $L_{178\ \mathrm{MHz}} \sim 2 \times 10^{33}$ erg s^{-1} Hz^{-1} (Fanaroff & Riley 1974). However, the distributions of the two radio classes overlap. From the point of view of their hosts, the two classes appear to habit different galaxies. FR Is are associated with 'red and dead' massive galaxies, while FR IIs show bluer color and larger amount of dust than FR Is (e.g., Baldi & Capetti 2008, Dicken *et al.* 2010).

In the distant Universe (z$\gtrsim$1), our comprehension of the RL AGN population is only based on studies on powerful radio galaxies. This is due to the classical selection bias which makes the flux-limited samples of distant radio galaxies abundant of FR IIs. Therefore, the global puzzle of the RL AGN population at high redshifts is missing an important piece. To obviate this problem, it is necessary to select carefully a sample of FR Is. Since our view of the radio morphology strongly depends on the depth of the radio observation, it is convenient to select distant FR I 'candidates', i.e. intrinsically low-power radio galaxies, at high redshifts. This is was the aim of the project of Chiaberge *et al.* (2009). They select the first sizeable sample of 37 FR I candidates at z$\gtrsim$ 1, located in the 2 deg^2 area of the sky observed by the COSMOS survey (Scoville *et al.* 2007). Taking advantage of the large multiwavelength coverage of the COSMOS data, we can perform a detailed analysis of the photometric properties of the host galaxies of these radio sources (details in Baldi *et al.* 2013).

2. Sample and data

The sample selected by Chiaberge *et al.* (2009) consists in 37 FR I candidates in the COSMOS field. This sample has been obtained with a four-steps multi-wavelength selection process. The first step consists of selecting radio sources from the FIRST catalog (Becker *et al.* 1995) whose 1.4 GHz total flux corresponds to the luminosities expected by FR Is at $1 < z < 2$. The second step consists of excluding all bona-fide FR IIs. The third step implies the optical identification of the radio sources in the COSMOS optical images. The objects associated with host galaxies brighter than $i = 22$ were rejected to exclude lower redshifts starburst galaxies. This step is based on the assumption that the properties of the host galaxies of distant FR Is are similar to those of distant FR IIs. As a final step, u-band dropouts are also rejected since these are objects most likely located at redshift higher than $z = 2$. The resulting sample consists of 37 FR I candidates. A posteriori, the photometric redshifts range of most of them is $\sim 1 - 2$ (Ilbert *et al.* 2009), with the exception of 3 objects that we exclude from any further analysis because out of the redshift range of interest. We are then left with a final sample of 34 objects.

The photometric data used are taken from the COSMOS survey. The COMSOS collaboration also provides different catalogs which give the magnitudes and the photometric redshifts, limited to $i < 25$, and spectroscopic redshifts for six sources. The radio data come from the FIRST and NVSS survey at 1.4 GHz.

3. Multiwavelength identification and SED

The multi-band identification of the hosts is a crucial point of the selection process. We carefully identify each counterpart in each band associated with the radio source in order to obtain its genuine emission. This would not be happened with a blind use of the COSMOS data. To carry out this multiband visual inspection, we basically use radio-optical-IR association to identify the correct counterpart. In case of misidentification with a spurious source or contamination from a nearby source we perform our $3''$-aperture photometry on the correct counterpart, possibly subtracting the erroneous emission.

Once we obtain all the correct magnitudes of each multiband counterpart, we can build up their SEDs from ~ 0.15 μm to 24 μm. To model the SEDs, we use two different template-fitting techniques: i) the *Hyperz* code (Bolzonella *et al.* 2000) that only considers single stellar templates and ii) our own developed technique *2SPD* that allows to include an old and young stellar population (OSP and YSP) and dust emission. We use Bruzual & Charlot (2009) and Maraston (2005) stellar templates.

4. Results

The *2SPD* code has turned out to more reliably model the SEDs of our sources than *Hyperz*, because the inclusion of YSP and dust component help the
fit to better reproduce the SED, crucially, in UV and MIR bands.

The first result of the SED modeling is the photometric redshifts. The resulting photometric redshifts range from $z \sim 0.7$ to 3 and are in substantial agreement between the two codes. Furthermore, they agree with the spectroscopic redshifts and with photometric measurements from earlier works (not all are included in the COSMOS photo-z catalog), but significantly more accurate due to our careful visual inspection of the counterparts. The normalized redshift differences ($\Delta z/(1 + z)$) are mostly smaller than 0.08.

The K-corrected (using a radio spectral index $\alpha = 0.8$) radio powers at 1.4 GHz measured with NVSS and FIRST are in the range $10^{31.5} - 10^{33.3}$ erg s^{-1} Hz^{-1}. Therefore, the radio distribution of our sample straddles the FR I/FR II break (Fig. 1). For simplicity,

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we separate the sample into two groups, including sources of high and low power (HP and LP, respectively) using the local FR I/FR II break as divide. Although HPs (one third of the sample) are as powerful as FR IIs, they can stil be possibly reconciled with FR Is, since the local RL AGN population shows cases of FR Is above the FR I/FR II break. The LP/HP separation also corresponds, not surprisingly, to a roughly division in redshifts: LPs are mostly at z $\lesssim$ 1.5.

Another important result from the SED modeling is the stellar masses of the hosts. The resulting stellar masses are mostly confined in the range $\sim 10^{10.5-11.5}$ $M_\odot$, with a median value of 7×10^{10} $M_\odot$. Due to the degeneration inherent to the modeling of SEDs the remaining results of the stellar populations are relatively unconstrained. However, we can generally claim that the SED of most objects of the sample is consistent with the presence of a dominant contribution from an OSP with an age $\sim 1-3$ Gyr with a small contribution of YSP of some Myr. However, significant excesses above the OSP are often observed at the shortest and/or longest wavelengths.

A dust component is needed to account for the 24 μm emission in 15 galaxies and significant excesses above the stellar emission are observed also at shorter IR wavelengths in 8 of these galaxies. Estimates of the dust luminosity yield values in the range $L_{\rm dust} \sim 10^{43.5}-10^{45.5}$ erg s^{-1}. The overall dust temperature, estimated for the 8 radio galaxies with a substantial dust excess at $\lambda \lesssim 8\mu$m, is in the range 300-850 K.

Inspection of the SEDs obtained with *2SPD* indicates that the UV excesses (above the contribution of the OSP) are often present (significantly in 15 sources and marginally in 7 sources), but they are usually weakly constrained. The UV luminosities measured at 2000 Å (rest frame) are in the range $10^{42}-10^{44}$ erg s^{-1}.

We can tentatively confirm the presence of positive links between the dust emission with both the radio and UV luminosities (excluding a redshift stretch of relations), although the censored analysis does not provide significantly high statistical parameters.

5. Discussion

The selection performed by Chiaberge *et al.* (2009) with the aim of searching for FR I candidates at z $\sim$ 1-2 turned out to be successful. In fact, our work confirms i) their location in the range of redshifts aimed with the selection process, although extending

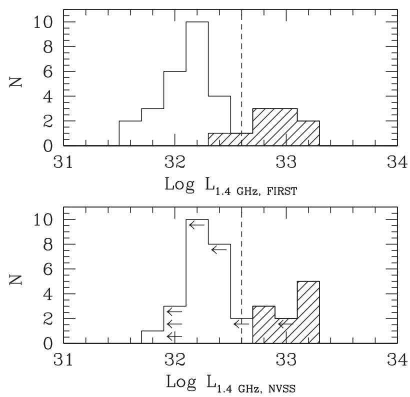

Figure 1. Distribution of the K-corrected total radio luminosity (in erg s^{-1} Hz^{-1}) at 1.4 GHz from the FIRST data (upper panel) and NVSS data (lower panel). The dashed lines corresponds to the local FR I/FR II break ($L_{1.4\,\rm GHz} \sim 10^{32.6}$ erg s^{-1} Hz^{-1}) used to separate the sample in high power (HP, shaded histograms) and low power (LP) sources.

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slightly below 1 and up to z ∼3 and ii) the low radio luminosity of the sample, generally consistent with those of the local FR Is, although 1/3 of the sample exceeds the local FR I/FR II luminosity break.

Overall, the hosts of these high-z low-luminosity radio sources are similar to those of the local FR Is which usually live in red massive early-type galaxies (e.g., Zirbel 1996; Best *et al.* 2005; Smolčić 2009; Baldi & Capetti 2010).

However, the SED modeling reveals that additional components to the OSP have to be included to account for the emission at the SED extremes, i.e. in either the UV or in the MIR band, in half of the sample. This behavior is not seen in the low-z FR I that are generally faint in UV (both from the point of view of star formation and nuclear emission, Chiaberge *et al.* 2002; Baldi & Capetti 2008). Similarly, their MIR luminosities exceed by a very large factor (between 30 and 3000 for the MIR detected sources) the typical low-z FR I luminosities ($\sim 10^{42}$ erg s^{-1}, Hardcastle *et al.* 2009). Conversely, the UV and MIR properties are somewhat similar to those of local FR IIs, which show bluer color (e.g., Baldi & Capetti 2008) and larger dust amount (e.g., de Koff *et al.* 2000; Dicken *et al.* 2010) than FR Is.

The origin of the UV and MIR component for those which show large excesses is plausibly ascribable to the presence of a quasar-like nucleus, as also supported by the high temperatures ($T \gtrsim 300$ K) estimated and their high radio powers. At the opposite end of the radio luminosity distribution, the other half of the sample are UV- and MIR-faint, similarly to the 'read and dead' galaxies and weak nuclei observed in the local FR Is. For the remaining sources the origin of the UV and MIR emission is not clear.

Summarizing, we find that the sources of the sample display a wide variety of properties, despite the relatively narrow range in radio luminosities. A further detailed analysis of the nuclear properties is needed to understand which type of AGN are associated with these high-z radio galaxies. This will include their X-ray emission (Tundo *et al.* 2012) and the radio core fluxes, available from the VLA-COSMOS data, but which we defer to a future study.

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