Galaxy Evolution and Feedback across Different Environments
Proceedings IAU Symposium No. 359, 2020
T. Storchi-Bergmann, W. Forman, R. Overzier & R. Riffel, eds.
doi:10.1017/S1743921320001866

Radio galaxies with and without emission lines

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Abstract. Using the recent ROGUE I catalogue of galaxies with radio cores (Kozieł-Wierzbowska *et al.* 2020) and after selecting the objects which are truly radio active galactic nuclei, AGNs, (which more than doubles the samples available so far), we perform a thorough comparison of the properties of radio galaxies with and without optical emission lines (galaxies where the equivalent width of Hα is smaller than 3Å are placed in the last category). We do not find any strong dichotomy between the two classes as regards the radio luminosities or black hole masses. The same is true when using the common classification into high- and low-excitation radio galaxies (HERGs and LERGs respectively).

Keywords. radio continuum: galaxies, galaxies: active, catalogs

1. Introduction

Recently, the first part of a catalogue of Radio sources associated with Optical Galaxies and having Unresolved or Extended morphologies (ROGUE I) has been published by Kozieł-Wierzbowska *et al.* (2020). It contains 32,616 spectroscopically selected galaxies from the Sloan Digital Sky Survey (SDSS; York *et al.* 2000) that have core identifications in the First Images of Radio Sky at Twenty Centimetre survey (FIRST: Becker *et al.* 1995, http://sundog.stsci.edu). The ROGUE II catalogue which will contain galaxies *without* cores is still in preparation, so here we present results based only on ROGUE I. This is by far the largest handmade catalog of this kind. Here we use it to revisit the differences between HERGs and LERGs previously discussed by many authors (eg. Best & Heckman 2012 and references therein). In Section 2 we briefly present the ROGUE I catalogue, in Section 3 we show how we extracted the radio AGNs. In Section 4 we recall several definitions of HERGs and LERGs and propose our own. In Sections 5 and 6 we compare the properties of the two classes.

2. The ROGUE I catalogue

The master sample is drawn from the 7th SDSS data release (Abazajian *et al.* 2009). It consists of the 662,531 galaxies from the Main Galaxy Sample and the Red Galaxy Sample for which the spectra have a signal-to-noise (S/N) ratio in the continuum at 4020Å larger than 10. Such a condition allows reliable determinations of parameters such as stellar masses, $M_\star$, black hole masses, $M_{\rm BH}$, emission-line intensities etc.

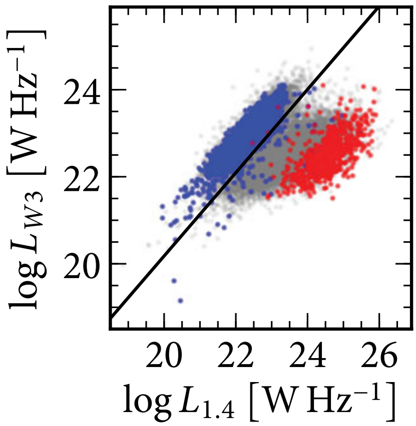

Figure 1. Diagram separating radio-AGNs from galaxies whose radio emission is related to star formation only. Blue points are star-forming galaxies according to the BPT diagram, red points are extended radio galaxies.

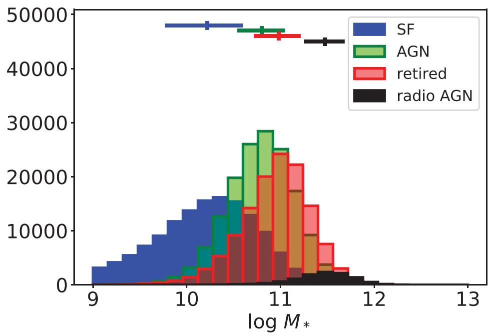

Figure 2. Histograms of stellar masses for the various galaxy types in the master sample.

The main products of the ROGUE I catalog are the identifications and redshifts of 32,616 radio sources associated to galaxies, the overlay maps, the total and core radio fluxes at 1.4 GHz, and a morphological classification in both the radio and the optical.

3. Extracting radio AGNs

ROGUE I contains both radio AGNs and sources whose radio emission is related to star formation only. It has been found (Kozieł-Wierzbowska *et al.* 2021, in preparation) that plotting the luminosities in the mid-infrared band W3, L_{W3}, versus the radio luminosities at 1.4 GHz, $L_{1.4}$, separates the two categories of radio sources very neatly (see Figure 1). Out of the 32,616 radio-sources in ROGUE I, 22,918 have a redshift $z < 0.3$ and can be plotted in this diagram. Out of those, 10,826 are radio-AGNs while 12,092 are in the star-forming branch (which also contains optical AGNs).

Figure 2 shows that, as expected, radio-AGNs are at the tip of the distribution of stellar masses in the ROGUE I master sample.

4. HERG and LERG definitions

Hines & Longair (1979), studying the spectra of 72 3CR galaxies, distinguished galaxies with strong emission-line spectra and those without strong emission lines. Later studies of the radio galaxies divided them into high- and low-excitation objects (HERGs and

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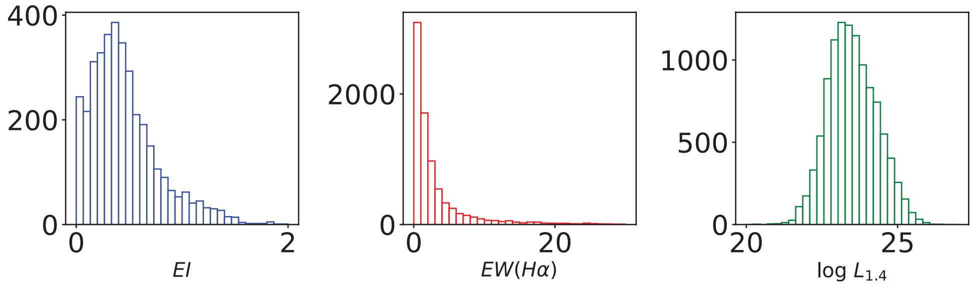

Figure 3. Histograms of the excitation index EI defined by Buttiglione, of EW(Hα), and of the total radio luminosities at 1.4 GHz, $L_{1.4}$, for our sample of radio galaxies. Note that the number of objects with EW(Hα) > 30, i.e. outside the limits of the histogram for EW(Hα), is around 200 only.

LERGs; see Padovani *et al.* 2017 for a review). These two classes have been suggested to correspond to different fueling modes of the AGN: a radiatively efficient mode through an accretion disk for HERGs and a radiatively inefficient mode through spherical accretion for LERGs (Heckman & Best 2014). The criteria used to distinguish HERGs and LERGs vary slightly among the authors. For example, Laing *et al.* (1994), studying a sample of 88 objects defined as HERGs those which had [O III]/H$\alpha > 0.2$ and EW([O III]) > 3 Å. Buttiglione *et al.* (2010) defined an excitation index $EI = \log$[O III]/H$\beta - 1/3(\log$[N II]/H$\alpha + \log$[S II]/H$\alpha + \log$[O I]/Hα), and considered as HERGs those objects having $EI > 1$. With such a definition, they found a clear bimodality in their sample of 113 objects. Best & Heckman for their study of 7302 objects devised a complex scheme and found an observational dichotomy, although with some overlap. More recently, Pracy *et al.* (2016) came back to a simpler scheme defining as HERGs those objects with S/N ([O III]) > 3 and EW([O III]) > 5 Å. Their sample contains 2221 objects with $z < 0.3$.

We propose to use a very simple classification, dividing radio galaxies into objects with and without emission lines. Among objects 'without' emission lines, we count those which have EW(Hα) < 3Å, since in this case the emission lines are likely due to ionization by hot low-mass evolved stars (HOLMES, Cid Fernandes *et al.* 2011). Although in the following, we still use the common HERGs/LERGs nomenclature, the real meaning of the division we propose is radio galaxies with or without an optical AGN.

5. HERGs versus LERGs in the ROGUE I sample

Fig. 3 shows the distribution of the excitation index EI defined by Buttiglione *et al.* (2010), of EW(Hα), and of the total radio luminosities at 1.4 GHz, $L_{1.4}$, for the 10,826 radio-AGNs of our ROGUE I sample. No dichotomy is apparent in our sample for any of those parameters.

It has been claimed that HERGs have larger radio luminosites than LERGs. The histograms plotted in Fig. 4 together with the values of the medians and quartiles show that the distributions of radio luminosities are indistinguishable between HERGs and LERGs, whatever definition of these categories is adopted.

The same applies for the black hole masses, as seen in Fig. 5.

In fact, among all the parameters tested the ones which show the largest difference between HERGs and LERGs are the stellar extinction, A_V (obtained by spectral synthesis fitting of the optical continua using the code *STARLIGHT* of Cid Fernandes *et al.* 2005) and D_{4000}, the discontinuity at 4000Å in the optical spectra. Both parameters are related to star formation: A_V indicates the presence of dust, implying the existence of cold or warm gas, while D_{4000} is an indicator of the mean age of the stellar population, being

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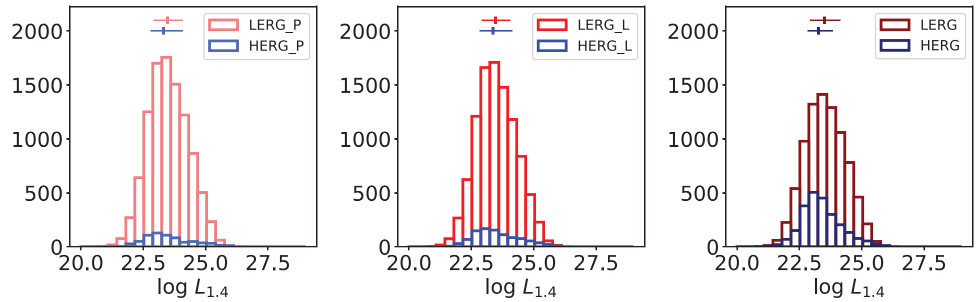

Figure 4. Histograms of total (i.e. including the lobes in case of extended sources) radio luminosities at 1.4 GHz for different definitions of HERGs (blue) and for LERGs (red). *Left panel:* definition of Pracy *et al.* (2016); *middle:* definition of Laing *et al.* (1994); *right:* our definition. The segments on top indicate the values of the medians and quartiles.

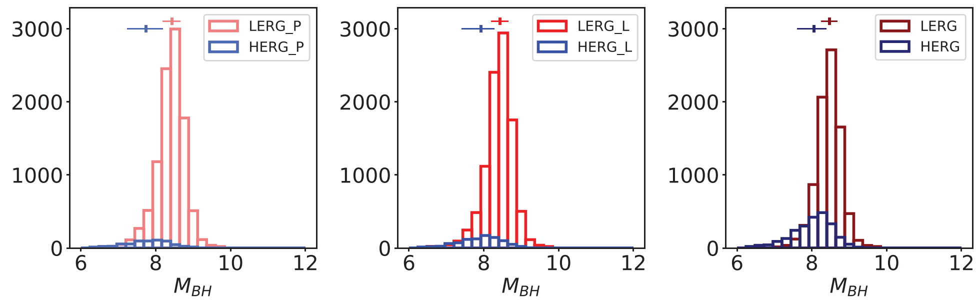

Figure 5. Histograms of the black hole masses for different definitions of HERGs (in blue) and for LERGs (in red).

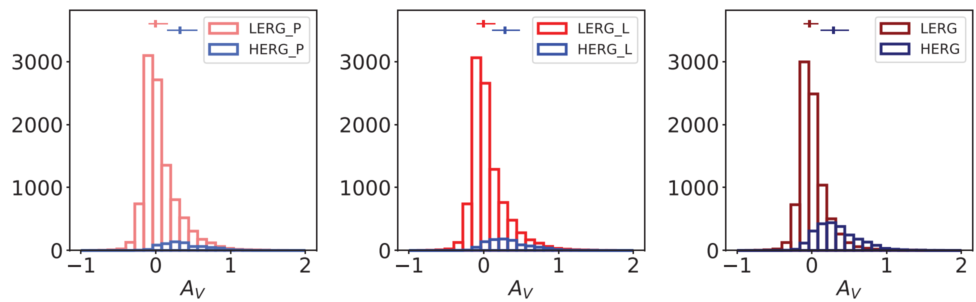

Figure 6. Histograms of the stellar extinction, A_V for different definitions of HERGs (in blue) and for LERGs (in red).

smaller in the presence of young stellar populations. The difference seen between HERGs and LERGs from these two parameters (see Figs. 6 and 7) indicates a larger amount of low-level star formation for HERGs. It must be noted, however, that the overlap is quite important.

6. HERGs and LERGs radio morphologies

Table 1 summarizes the radio properties and Figure 8 shows the distribution of radio morphologies in the HERG and LERG samples (using our definition of HERG and LERG). The vast majority of the objects are compact (ie. unresolved), or elongated (ie. one-component source with one deconvolved dimension larger than zero).

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Table 1. HERG and LERG morphologies.

number ratio	HERGs	LERGs
compacts / extended	23	10
FRII / FRI	6.2	2.4

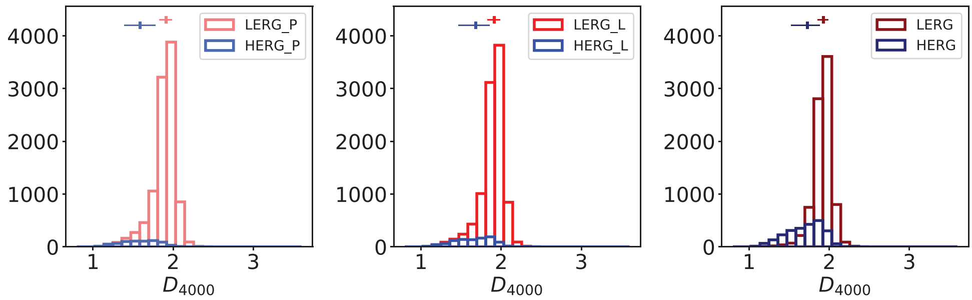

Figure 7. Histograms of the discontinuity at 4000Å, D_{4000}, for different definitions of HERGs (in blue) and for LERGs (in red).

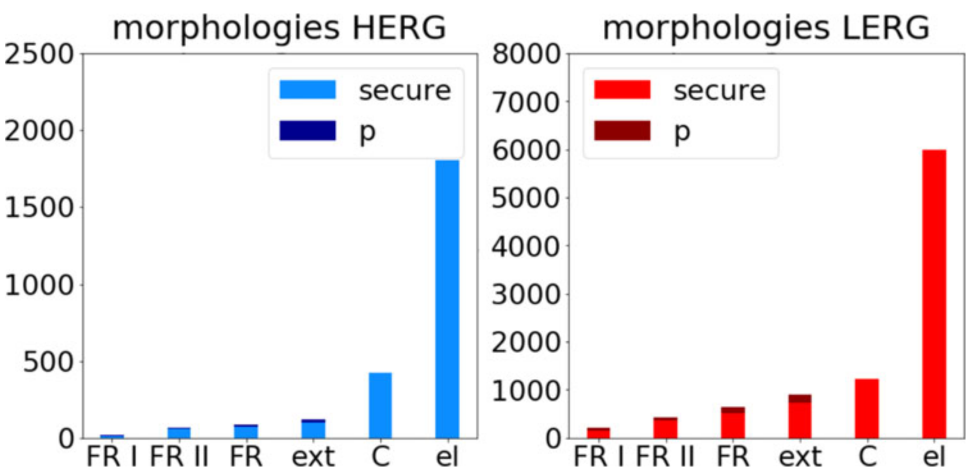

Figure 8. Distribution of radio morphologies among HERGs and LERGs. 'FR' stands for FR I, FR II and FR I/II; 'ext' stands for all the extended morphologies, including FR, one-sided, double-double, X-type etc.; 'C' stands for compact; 'el' stands for elongated; 'p' stands for possible, meaning that the classification is less secure.

The proportion of extended radio sources is larger for LERGs than HERGs, as is the proportion of FR I with respect to FR II.

A detailed version of this work will be published including the results from ROGUE II, the catalogue of radio sources without radio cores (in preparation).

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