Perseus in Sicily: From Black Hole to Cluster Outskirts
Proceedings IAU Symposium No. 342, 2018
K. Asada, E. de Gouveia Dal Pino, M. Giroletti,
H. Nagai & R. Nemmen, eds.
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doi:10.1017/S1743921318005537

Life-cycles & Energetics of Radio-Loud AGN

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Abstract. Radio jets are the large-scale and extragalactic footprints of accretion onto supermassive black holes, and are suggested to be the key ingredient controlling the galaxy stellar mass function. Of particular importance is their jet power - the time-averaged energetic feedback into their environment. Hence, the dynamics, energetics and life-cycles of radio-loud AGN (RLAGN) must be understood in order to build a qualitative and quantitative picture of their impact over cosmic time. Here, we present a study of the spectral age of two powerful, cluster-center radio galaxies, and compare with an analytic model to robustly determine their jet powers. We also present some recent LOFAR observations of the different phases of RLAGN activity, namely the remnant and subsequent restarting phases, which are key to understanding the dynamics of RLAGN over their total lifetime.

Keywords. galaxies: jets, galaxies: nuclei, radio continuum: galaxies

1. Introduction

Radio galaxies or RLAGN drive powerful jets into their surrounding environment. This can have profound implications for cosmic evolution: the well known AGN feedback mechanism (e.g. Croton *et al.* 2006; Wyle *et al.* 2016) attempts to account for the shape of the galaxy stellar mass function – there is a steep decline of galaxies with increasing stellar mass. This can naturally be explained if heating by AGN outflows suppresses star-formation in the most massive galaxies (e.g. McNamara & Nulsen 2007), while this mechanism can also similarly explain the lack of cold gas at the centres of the thermal intra-cluster medium (ICM) in galaxy clusters (Smith *et al.* 2002; Mingo *et al.* 2014). It is therefore important to understand and quantify the energetics of radio galaxies over their lifetime.

The jet power, the time-averaged energetic output of the radio source, is therefore a crucial ingredient of galaxy and cluster evolution models. The determination of the jet power, however, requires an accurate estimate of the age of the radio source, which historically has been difficult to obtain. An estimation of the dynamical age of the source requires some model of the lobe advance speed, which itself is a time-dependent value since the radio jets are expected to decelerate on large scales due to their dense environments. On the other hand, the physical process of spectral ageing (discussed below), has been invoked to determine the age of the radio source, although traditionally the spectral age of a given radio galaxy almost always seems to be underestimated relative to its dynamical age (e.g. Eilek 1996; Harwood *et al.* 2013; Harwood *et al.* 2015).

With future wide area radio surveys (e.g. the LOFAR Two-Metre Sky Survey, ASKAP, MeerKAT and eventually, the SKA itself) on the horizon, it is essential that methods and techniques used to determine jet powers are available, in order to quantify the energetic impact of the population of RLAGN. Low-redshift studies of powerful sources are the necessary precursors for these future population-based studies.

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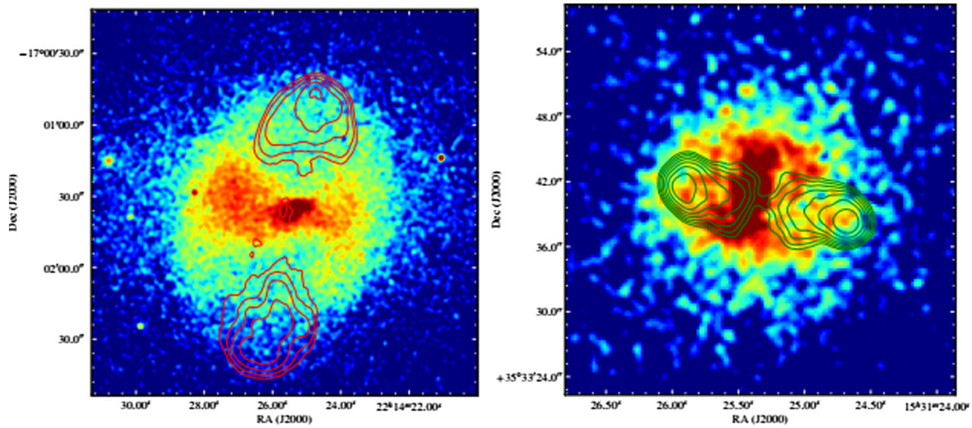

Figure 1. X-ray *Chandra* observations of the cluster environments of 3C444 and 3C320, with contours from archival observations of the radio source overlaid.

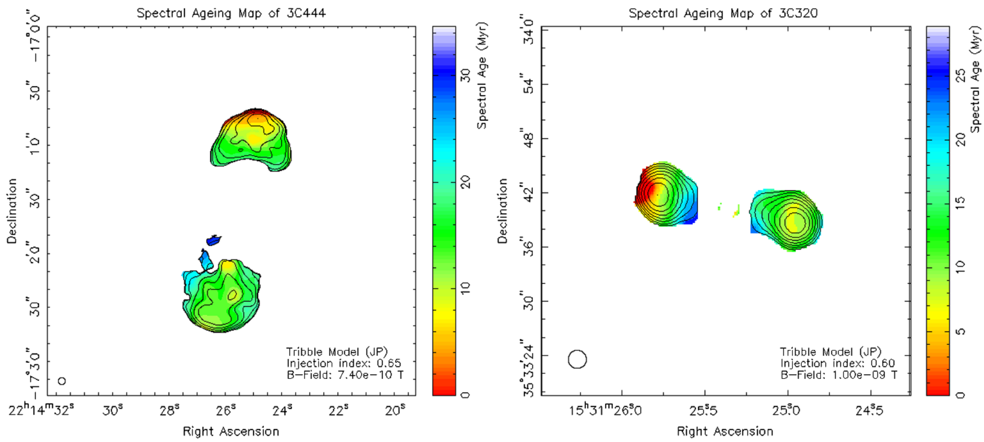

Figure 2. Spectral age maps of 3C444 and 3C320 produced by BRATS Harwood *et al.* (2013).

2. Spectral ageing

Spectral ageing is the radiative cooling process by which the particles in the lobes of radio galaxies emit synchrotron emission. This produces a distinct and characteristic (age-dependent) spectrum at GHz radio frequencies, and can be used to determine the age of the population of electrons in the lobe producing the emission.

3C320 and 3C444, two powerful radio galaxies sitting in rich cluster media emitting hot X-ray gas (see Figure 1), were observed with the VLA in its broad-band setup at multiple array configurations, and at 1.4 GHz and 6 GHz, producing well sampled data sets with a broad frequency coverage enabling robust measurements of their lobe spectra. Using the `BRATS` software package (Harwood *et al.* 2013), which fits contemporary models of ageing spectra to the observed spectra on a pixel by pixel basis, we determined the spectral ages of 3C320 and 3C444 and, for comparison purposes, their dynamical ages based on a model of the lobe advance speed using X-ray Chandra data. Their spectral and dynamical ages agree relatively well, based on certain assumptions regarding the lobe magnetic field strengths and X-ray shock dynamics, contrary to previous studies on the discrepancy of spectral and dynamical ages.

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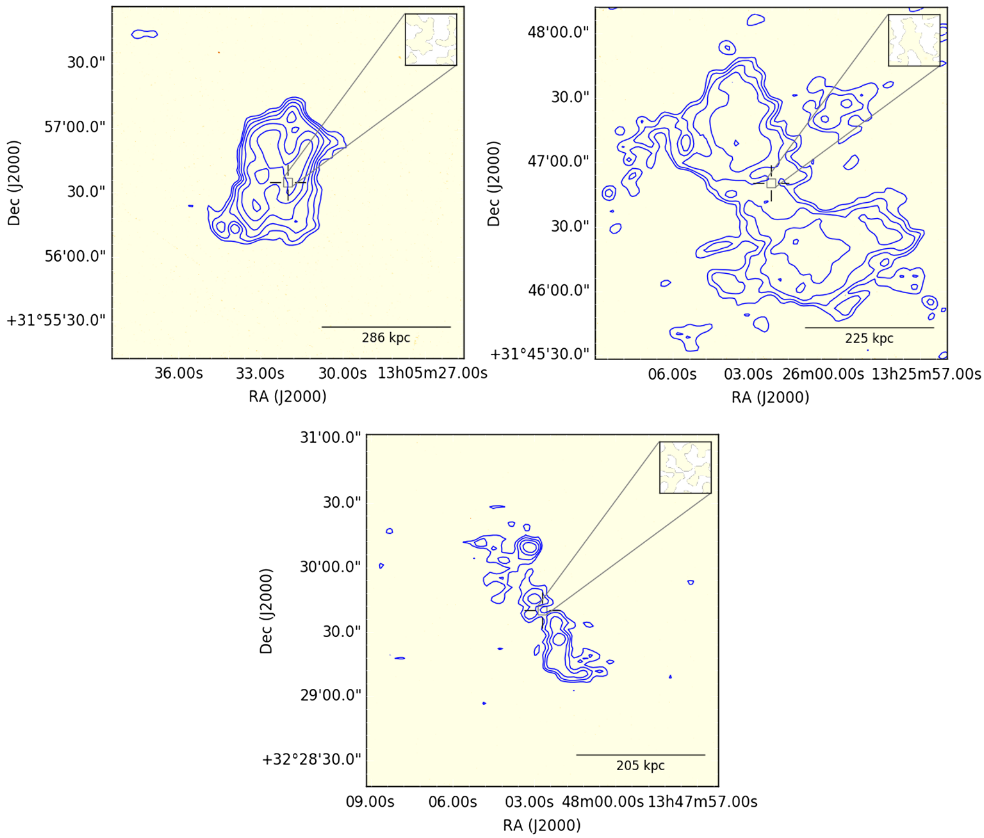

Figure 3. LOFAR observations of candidate remnants in the Herschel-ATLAS field (Mahatma *et al.* 2018) (blue contours) overlaid on follow-up VLA observations showing a lack of a radio core – see zoom-in.

To test the spectral ageing model in determining accurate ages, we use the model of Hardcastle (2018) – a simulation based analytic model of the evolution of radio galaxies. Using physical source parameters based on our observations, we produced a model for the time-evolution of 3C320 against physical source parameters such as radio luminosity and source size, as a function of jet power. We obtained self-consistent dynamical models that agree with our radio and X-ray measurements, and they show that the spectral age/dynamical age discrepancy increases as the lobe magnetic field goes towards the equipartition value. This shows that the lobes of radio galaxies are not in equipartition, agreeing with many previous studies. Our spectral ages are therefore robust, and give accurate determinations of jet powers of radio galaxies.

Of further importance are the jet powers of the population of RLAGN. Hardcastle *et al.* (2019) inferred the jet kinetic luminosity function, essentially the number density of sources as a function of jet power, for the ($\sim 23,000$) objects selected as RLAGN from the LOfar Two-metre Sky Survey (LoTSS: Shimwell *et al.*, submitted, Duncan *et al.* 2019, Williams *et al.* 2019) of the HETDEX field. Their result that RLAGN as a population, with jet powers inferred from their radio luminosities and an assumption of their environment, produce sufficient energy to overcome radiative cooling of the hot, X-ray emitting gas in the centers of clusters is an important requirement of AGN feedback models. Even with these advances, the energetic impact of the other evolutionary phases

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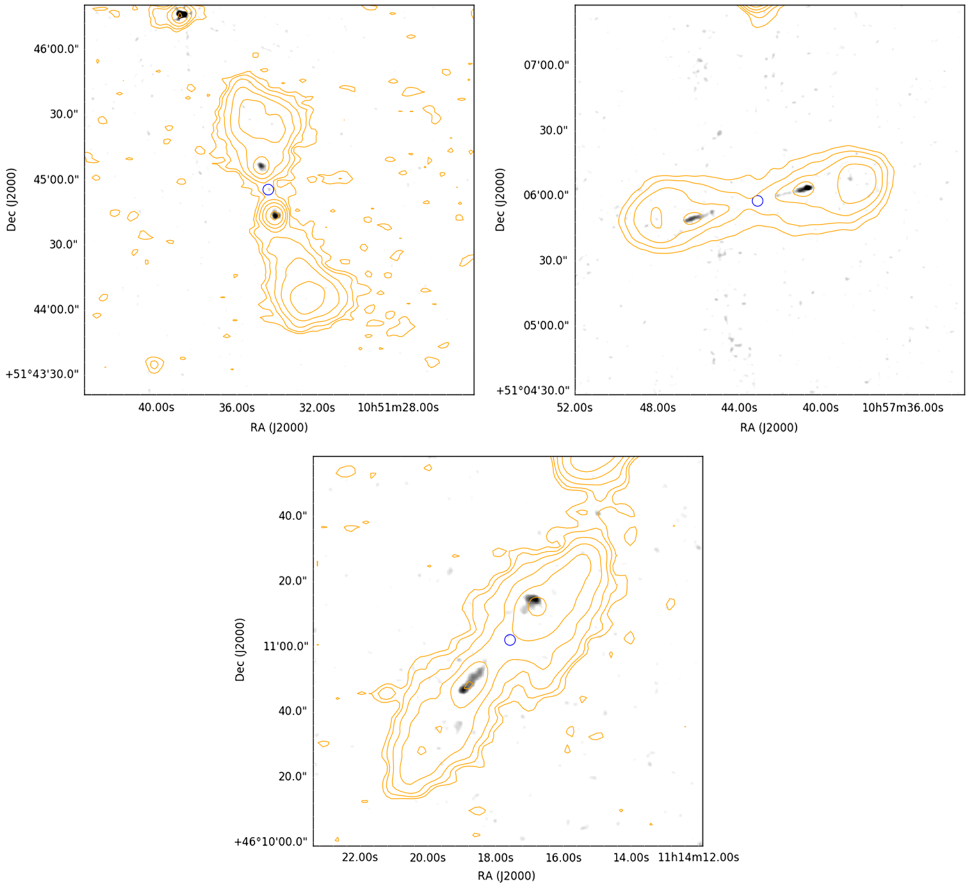

Figure 4. LOFAR observations of DDRGs in the HETDEX field (Mahatma *et al.*, submitted) (orange contours) overlaid on follow-up VLA observations (gray-scale) confirming the presence of inner jets.

of RLAGN are far less understood, namely the remnant (switched off) and restarting phases, observations of which have been severely limited in the past.

3. Remnant and Restarting Radio-Loud AGN

With the current best low-frequency radio telescope at ~ 5 arcsec resolution capable of wide-area observations, LOFAR, RLAGN are beginning to be observed down to low radio luminosities ($L_{150} \sim 10^{24}$ W Hz^{-1}) (Hardcastle *et al.* 2019). Studies of such low surface brightness sources have given the opportunity for large-sample studies of the remnant and subsequent restarting phases of radio galaxies – crucial to our understanding of the overall impact of RLAGN.

LOFAR observations in *Herschel*-ATLAS field (Hardcastle *et al.* 2016) have enabled candidate remnant RLAGN to be captured, and sampled on a systematic level (Mahatma *et al.* 2018), a few of which are shown in Figure 3. Crucially, the remnant fractions of ~ 10 per cent found by Brienza *et al.* (2017), Godfrey *et al.* (2017) and Mahatma *et al.* (2018) imply a rapid fading process for the synchrotron plasma left behind by the previously active AGN.

RLAGN, particularly for the class of low-excitation radio galaxies (LERGs: e.g. Hardcastle *et al.* 2007), are expected to restart some time after the beginning of the

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remnant phase. The class of double-double radio galaxies (DDRGs: Schoenmakers *et al.* 2000) are the most clearly visible restarting sources found in radio observations, showing two pairs of radio lobes – an inner pair denoting the restarted active jets, and an outer pair denoting the remnant lobes from the previous activity. One of the outstanding questions surrounding the nature of DDRGs is what causes the jets to switch to a remnant and subsequent restarting phase: if the host galaxies of DDRGs are significantly different in physical appearance, such as in their integrated stellar emission or colour, which may be caused by galaxy mergers, then a host galay dichotomy between DDRGs and single-cycle RLAGN should exist. With the first data release of LoTSS, compromising of LOFAR observations in the HETDEX field at 6 arcsec resolution with a median sensitivity of 70μJy beam^{-1}, we visually identified a sample of 40 DDRGs, with follow-up VLA observations at 1.3 arcsec, which confirmed the presence of inner edge-brightened jets typical of the restarted jets of DDRGs, and hence allowed us to confirm or reject DDRGs in our sample. With a final robust sample of 33 DDRGs (a few of which are shown in Figure 4), we compared their host galaxy properties with those of the RLAGN sample of Hardcastle *et al.* (2019), matched in radio luminosity. We find that the host galaxy rest-frame absolute magnitudes and colours (optical and near infra-red K_s, r and $WISE$ bands) for the DDRGs are indistinguishable compared to RLAGN. This confirms, particularly for LERGs which perhaps dominate our selection samples, that restarted activity is not driven by significant changes in the host galaxy, and is therefore a normal process in the lifetime of powerful RLAGN.

These findings have constrained useful information on the nature of RLAGN and their various phases of evolution. With the upcoming data release of LoTSS, and the advent of future wide-area sensitive radio surveys such as the SKA, high fidelity observations of radio galaxies will routinely be available, enabling further insights into the energetics and lifetimes of RLAGN.

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