DYING RADIO GALAXIES IN CLUSTERS

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Abstract

We report the recent discovery of three 'dying' radio galaxies belonging to the Westerbork Northern Sky Survey minisurvey sample: WNB1734+6407, WNB1829+6911 and WNB1851+5707. These sources have been selected on the basis of their extremely steep broad-band radio spectra, which is a strong indication that these objects either belong to the rare class of dying radio galaxies or that we are observing 'fossil' radio plasma remaining from a previous nuclear activity. Deep spectral index images obtained with the Very Large Array confirmed that in these sources the central engine has ceased to be active for a significant fraction of their lifetime although their extended lobes have not yet completely faded away. In one case, WNB1829+6911, fossil radio lobes are seen in conjunction with newly restarting jets. We found that each source is located (at least in projection) at the center of an X-ray emitting cluster. We argue that their intriguing association with clusters implies that the pressure of the dense intracluster medium, perhaps a cooling flow, prevents quick liquidation of a fossil radio lobe through adiabatic expansion. On statistical ground we deduce that the duration of the dying phase for a radio source in cluster is one order of magnitude higher with respect to that of a radio galaxy in the field.

1 Introduction

Strong radio sources, associated with elliptical galaxies, are supplied with energy from active galactic nuclei via plasma beams. If this energy supply ceases, a source is expected to undergo a period of fading before it disappears completely. In this phase, sources may lack certain features, such as radio cores or well-defined jets that are commonly interpreted as indicators of continuing activity. Alternatively, it is possible that radio galaxies may be active intermittently. In this scenario, one expects to observe fossil radio plasma remaining from an earlier active epoch, along with newly restarting jets. The best case for fossil radio lobes seen with a currently active galaxy is 3C338 (Jones & Preston 2001). The very steep spectrum lobes of this source are clearly disconnected from the currently active jets. In both scenarios, the fading lobes are expected to have very steep ($\alpha > 1.5$, $S_\nu \propto \nu^{-\alpha}$) and convex radio spectra characteristic of a population of electrons which have radiated away much of their original energy (Komissarov & Gubanov 1994). Only a handful of fossil radio galaxies with the characteristics described above are known (e.g., Cordey 1987, Venturi et al. 1998). In their sample of radio sources, selected from the B2 and 3C catalogs, Giovannini et al. (1988) found that only a few percent of objects exhibit the characteristics mentioned above. A possible explanation for the rarity of the fading radio galaxies may be the short duration of the remnant phase of a radio source with respect to the average lifetime of the radio activity. Synchrotron losses and the inverse-Compton scattering of the cosmic microwave background photons preferentially deplete the high-energy electrons. In the absence of fresh particle injection, the high-frequency radio spectrum develops an exponential cutoff. At this point, the adiabatic expansion of the radio lobes will concur to shift this spectral break to lower frequencies and the source will disappear quickly. On the other hand, if the source expansion is somehow reduced, or even stopped, there is still the chance to de-

Table 1: Dying radio galaxies and their hosting clusters

WENSS name	ID	Cluster	redshift†	$S_{1.4\ \mathrm{GHz}}$ mJy	$\alpha^{\ddagger}_{1.4\ \mathrm{GHz}}$	LAS $''$	LS kpc	$L_{151\ \mathrm{MHz}}$ W Hz^{-1}
WNB1734+6407	G	A2276	0.1406	7.2	2	50	122	$10^{25.4}$
WNB1829+6911	G	ZwCl 1829.3+6912	0.204	12.6	1.9	40	133	$10^{25.9}$
WNB1851+5707	G	RXC J1852.1+5711	0.109	53.3	1.7	20	39	$10^{25.3}$

†We adopted a cosmology with H_0 = 71 km s^{-1} Mpc^{-1}, Ω_Λ = 0.73 and Ω_m = 0.27.
‡Spectral indexes and flux densities refer to integrated values.

tect the fossil radio lobe, at least at low frequency. It is important to note that these sources represent the last phase in the 'life' of a radio galaxy. Therefore they must be well distinguished from the cluster radio halo/relic phenomenon, that is usually not associated with an individual galaxy (Slee et al. 2001).

2 Source selection and integrated spectra

For the reasons mentioned above, the Westerbork Northern Sky Survey (WENSS) at 327 MHz is particularly well-suited to search for these elusive fossil radio sources. A sub-sample, the WENSS minisurvey (de Ruiter et al. 1998), contains 400 radio sources identified with either elliptical or spiral galaxies with red magnitude brighter than m_r = 16.5. Using cross-correlation with the existing catalogs and new observations with the Effelsberg 100-m telescope, we have obtained spectral information in the frequency range 38 MHz to 10 GHz for 200 bright sources. Three out of 200 sources show extremely steep spectra which are characterized by a quasi-exponential drop above a frequency of about 1 GHz. These are WNB1734+6407, WNB1829+6911, WNB1851+5707 (see Table 1 and Fig. 1).

We have fitted the spectral aging model of Komissarov & Gubanov (1994) to the extremely steep broadband radio spectra of the three sources. They assumed a finite duration for the continuous injection (CI) of relativistic electrons, t_CI, followed by a relic phase (RE) of duration t_RE. During both the CI and the RE phase, the electrons lose energy by synchrotron emission and inverse-Compton scattering of cosmic microwave background photons. The fit of the Komissarov-Gubanov model to the radio spectra support the scenario in which the injection of fresh electrons in these sources has ceased for a significant fraction of their lifetime ($t_\mathrm{RE}/t_\mathrm{CI} \sim$ 0.5–0.7).

3 Very Large Array spectral index imaging

In order to determine whether these sources were really dying objects or relic lobes associated with active radio galaxies, we observed their radio continuum emission at 20 and 6 cm with the Very Large Array (VLA) in various configurations. These extensive campaign of observations allowed us to obtain very deep spectral images of matched angular resolution, see right panels of Fig. 2. We achieved a noise level of about 10 μJy beam^{-1} and an angular resolution of 6$''$ at both frequencies. For all three sources, the deep VLA images confirmed beyond any doubt the presence of fossil radio plasma from an earlier nuclear activity. It is worth noting that all these radio sources have a firm optical identification with an elliptical galaxy, but, at the sensitivity limit of our observation, none of them possesses radio jets on kiloparsec scale.

Characterized by two relaxed lobes lacking hotspots, the radio morphology of WNB1734+6407 resembles that of B2 0924+30 which is considered the prototype of fossil radio galaxies (Cordey 1987). The radio spectra of the fossil lobes of WNB1734+6407 is so steep that their surface brightness at 6 cm is below the sensitivity level of our observations. Thus, we can only place lower limits on the spectral index which result in $\alpha > 3.3$ and $\alpha > 2.1$ for the northern and southern lobe, respectively. We also observe a slightly extended component coincident with the galaxy core. This feature a very steep spectral index, α = 1.8. Its nature remains unclear.

The radio appearance of WNB1829+6911 is virtually identical to that of 3C338, a nearby radio source associated with the central dominant galaxy in the cooling flow cluster Abell 2199. In both sources we observe the presence of fossil plasma remaining from a previous activity in conjunction with a restarting core.

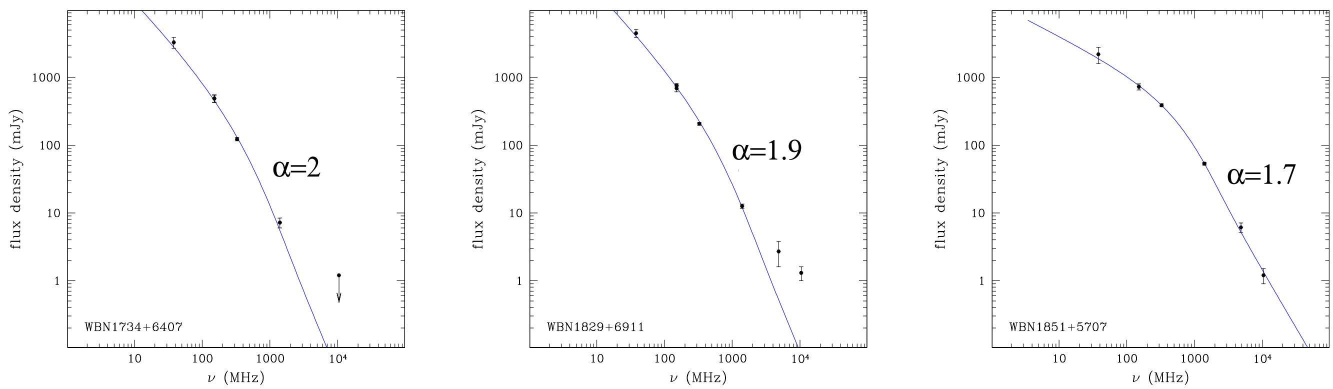

Figure 1: The ultra-steep spectra of WNB1734+6407, WNB1829+6911 and WNB1851+5707. Compare with the typical active radio galaxies which have power law spectra with $\alpha \simeq 0.8$. The solid lines represent the best fit of the Komissarov-Gubanov model (see text). The relative durations of the relic phase ($t_{\rm RE}$) with respect to the active phase ($t_{\rm CI}$) are in the range 0.5–0.7.

The extended emission of WNB1829+6911 has a very steep spectrum, $\alpha > 2.2$. The source exhibits a bright core with a much flatter spectrum, $\alpha = 0.6$. Most probably this region of the radio source is powered by a new couple of restarting jets. The core emission is responsible for the high-frequency flattening seen in the source integrated spectrum (Fig. 1).

Finally, our VLA images reveal that WNB1851+570 is in reality composed of two distinct fossil radio galaxies. For both source we measured a spectral index $\alpha = 2.3$. Given the rarity of these sources, this association is quite intriguing.

Some physical parameters of the sources are listed in Table 1. The calculation of the source power at 151 MHz, where the energy losses of the synchrotron electrons are less dramatic, place them near the FRI-FRII division (Fanaroff & Riley 1974).

4 The X-ray environment

We have also made a search in the *ROSAT* All-Sky Survey (RASS) for possible X-ray counterparts. Each source is located, in projection, at the center of an X-ray emitting cluster (see Table 1 and Fig. 2 left column panels).

The gaseous environment in which radio galaxies are embedded affects their morphology and regulates their expansion. These effects are particularly important in clusters of galaxies, where radio galaxies and the X-ray-emitting intracluster medium (ICM) influence each other profoundly. The ICM confines and distorts radio lobes and causes the jet bending. At the same time, high resolution *Chandra* images have shown that the lobes of central radio galaxies inflate cavities in the ICM of many cooling flow clusters (e.g., McNamara et al. 2000, 2001; Blanton 2001; Heinz et al. 2002, Johnstone et al. 2002), which is currently the favored mechanism for the suppression of cooling flows (e.g., Churazov et al. 2000; David et al. 2001; Böhringer et al. 2002). Here we point out that interactions between the radio galaxies and the ICM may have drastic and interesting consequences at the final stages of a radio source's life. The simplest explanation for the association of our dying radio galaxies with cluster is that the pressure of the dense ICM, perhaps a "cooling flow", prevents quick dissipation of the radio source through adiabatic expansion. If so, it is likely that the signs of the interaction between the radio plasma and the surrounding gas have survived in the form of X-ray cavities in the ICM. Our fossil sources might be the progenitors of 'ghost' bubbles, the buoyantly rising X-ray cavities that are not associated with the central radio sources, such as those recently discovered by McNamara et al. (2001) in A2597.

In order to test this hypothesis, we have proposed *Chandra* observations to compare the actual fading radio structures with the X-ray image of similar angular resolution.

5 Statistical analysis

The space density of powerful radio galaxies deduced from a complete sample can be used to derive stringent upper limits to radio source lifetimes (e.g., Schmidt 1966). In the WENSS minisurvey sample we count 90 radio galaxies with red magnitudes brighter than $m_{\rm r} <$

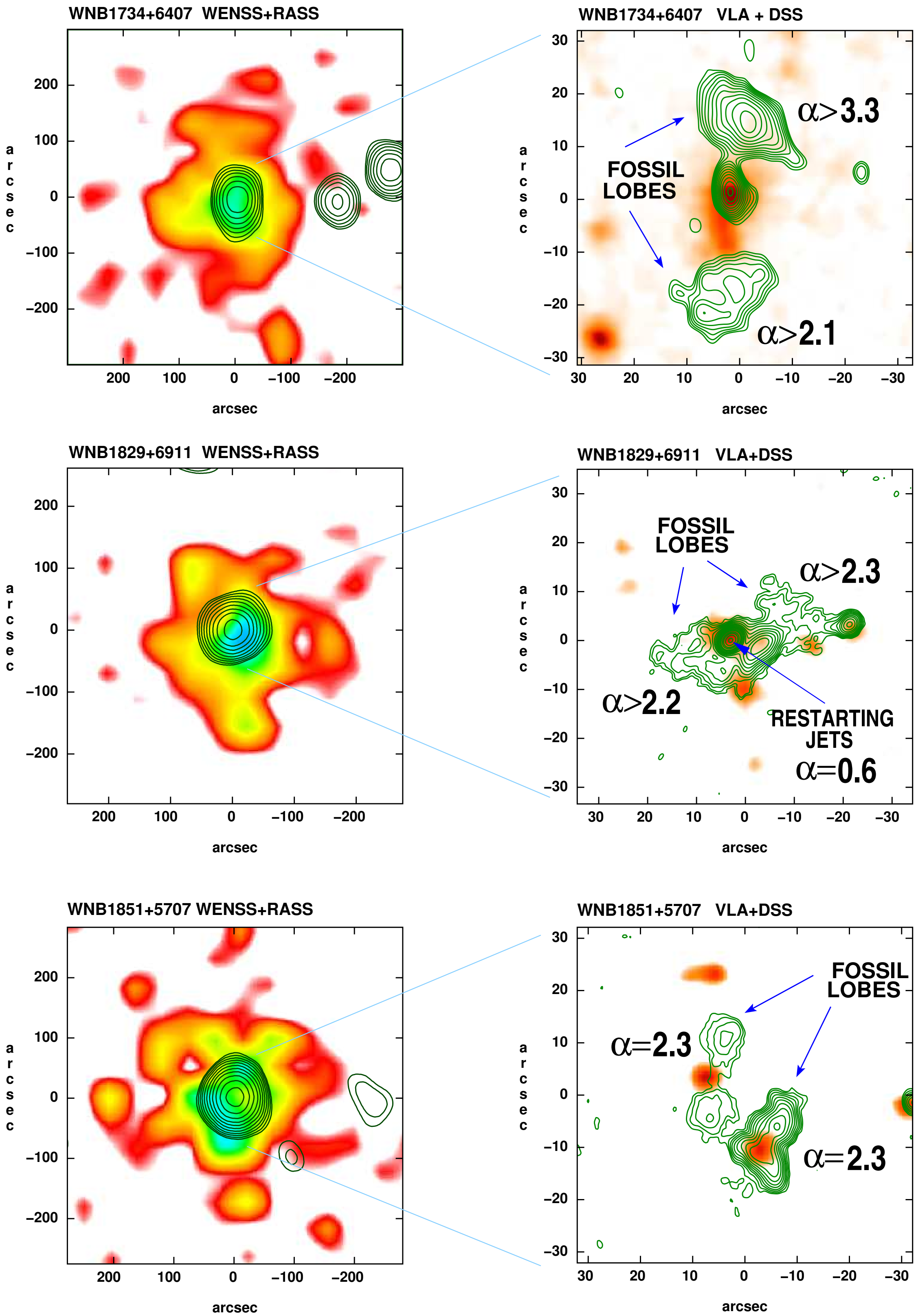

Figure 2: Left panels: overlays of the WENSS (contours) and RASS (gray-scale). Right panels: overlays of the VLA 1.4 GHz contours with the optical images taken from the Digitized Sky Survey. The only plausible explanation for the extremely steep spectrum of the fossil lobes is that the injection of relativistic electrons in these components is short compared to the lifetime of the source (see text).

16 with a flux density at 327 MHz greater than 30 mJy. Of them, $N_{\rm clr}$ = sources are found inside bright X-ray emitting clusters of galaxies in the list of Böringer et al. 2000. Two of them are dying sources. Taking into account the volume occupied by the radio sources in cluster of galaxies and by the dying sources we find a density ratio of 0.6. This means that the relic phase *in clusters* lasts for about 60% of the active phase duration. We note that this estimate is in good agreement with the radiative ages deduced from the integrated spectra (Sect. 2). We repeated this calculation by considering the radio galaxies in the B2 sample that lie outside rich Abell galaxy clusters. In this case the density ratio of the volume occupied by the dying sources to the volume occupied by the total number of radio sources outside galaxy clusters is 0.06. The relic phase duration for a radio galaxy in the field results to be only 6% of the source lifetime. These statistical considerations indicate that the probability to observe a dying radio galaxy in clusters is therefore increased by a factor of about ten.

Acknowledgments

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